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Strange Repercussions of Röntgen's Discovery of the X-Rays

OTTO GLASSER, Ph.D.

Research Division, Cleveland Clinic, Cleveland, Ohio

In events that followed the discovery of the x-rays in 1895 and in their discoverer's reaction to these events is material for a psychological study of the effect on Wilhelm Conrad Röntgen of public acclaim and criticism. It is interesting that Röntgen assiduously avoided exposing himself to acclaim and reacted in an almost exaggerated manner to criticism.

At the time of the discovery of the x-rays, physicists complacently accepted the fact that there was little new to be discovered in physical science and accordingly strove mostly to attain greater accuracy in physical mensuration. For no obvious reason Röntgen was an exception. In March 1895, he was fifty years of age and well situated as professor of physics at the Julius-Maximilian's University in Würzburg. Forty-eight papers published in the previous twenty-five years attested to the originality of his findings in physical research. His report of the electrodynamic effects of a dielectric moved through a homogeneous electrical field, for example, had so impressed his colleagues that they suggested calling the current thus produced the "roentgen current." In the academic world he had a record of similarly satisfactory achievement, and the previous year he had been elected to the highest office of the university, that of rector. Yet with youthful enthusiasm, late in 1895, he turned his full attention to researches on the cathode rays, along the lines laid down by Hittorf and Crookes and by Hertz and Lenard.

The systematic reproduction of previous cathode-ray experiments and the subsequent tracing of the fluorescent effect produced by something emanating from an excited Hittorf-Crookes tube led to the discovery of a new kind of rays, the x-rays. The analysis of this new effect and the investigation of all its ramifications as reported in his three classic papers on *A New Kind of Rays* (1) reveal Röntgen to be one of the greatest scientists of all time. He was immediately and widely acclaimed. Yet almost simultaneously voices of criticism were heard. With a certain bravado, Röntgen wrote to his good friend Zehnder (2) shortly after the announcement of the discovery:

> "My work has received recognition from many quarters. . . . This is worth a great deal to me, and I let the envious chatter in peace; I am not concerned about that."

Doubtless because of the rapidity with which the news of the discovery was spread and the sensational manner in which most of the early reports were presented, Röntgen suffered in adjusting to the publicity, which, as it soon became evident, he wished to avoid (3). Only a few of the honors traditionally awarded to distinguished men did he care to receive personally; one of these was the first

Nobel prize ever awarded in physics, for which he traveled to Stockholm in 1901. Even this was but a half measure, in that he refused to give a Nobel lecture. His first lecture on the x-rays, delivered at the earnest request of his colleagues at the Physical Medical Society of Würzburg on Jan. 23, 1896, was probably the only public lecture he ever gave on his great discovery.

Early claims to priority in the discovery of the x-rays were partly activated by the bringing to light of certain uninvestigated accidents caused by the rays. Sir William Crookes, whose cathode-ray type tubes Röntgen had used in many of his experiments, had observed that unopened boxes of photographic plates were fogged and had complained repeatedly to the manufacturer of their unsatisfactory quality. That this effect was actually due to x-rays he did not know until Röntgen's discovery had been announced. Others had had similar experiences with x-ray plates but had only drawn the conclusion that it was advisable to store the plates some distance from the tubes (3).

Many early cathode-ray workers, as Lenard once stated (4), had observed a great number of new phenomena, but these phenomena were never followed up. The Philadelphia physicist Goodspeed had accidently made an x-ray picture over five years before the x-rays were discovered (3) and was unable to explain the phenomenon until Röntgen's observations were reported.

Although most scientists gave Röntgen full credit and the honor that were his due, a whispering campaign was started that the discovery was an accident and that the first crucial observation of the fluorescence of the screen was made by an assistant or a *Diener*. The best answer to these rumor mongers was given by Münsterberg of Harvard, who in reporting his views on the discovery to *Science* on Jan. 15, 1896, wrote:

> "Suppose chance helped. There were many galvanic effects in the world before Galvani saw by chance the contraction of a frog's leg on an iron gate. The world is always full of such chances, and only the Galvanis and Röntgens are few."

Still, the silly rumors persisted throughout Röntgen's life. With advancing years he retired behind a protective screen and eventually became very bitter. Two far reaching effects of his bitterness were his refusal to publish anything further on the rays after his three original communications and the stipulation in his will that all records of his work and all correspondence about the discovery between 1895 and 1900 be burned unopened at his death, a decision which—unfortunately—had to be carried out to the letter. There is no doubt that vicious attacks which appeared from time to time—an especially violent one was published in the *Münchner Post* in 1908—were responsible for these decisions. A few years before his death, in April 1921, Röntgen expressed his feelings to his old friend and collaborator, Zehnder, in the following words:

> "The infamous rumor that I did not discover the rays originated presumably in Quincke's institute in Heidelberg. . . . "

And at the same time he wrote to the wife of his late best friend, Theodore Boveri:

> "Zehnder also heard the fable that I was not the first to notice the x-rays, but that an assistant or *Diener* discovered them. What miserable envious soul must have invented this story?"

Years later the slandering rumors had not died down. In 1935, twelve years after Röntgen's death, an entirely uncalled-for article appeared in the *Zürcher Illustrierte*, a Swiss weekly. The article, by one E. Grieder, entitled *The Real Facts of the Discovery of the X-Rays,* was not only slandering but full of historical inaccuracies.

After a careful scrutiny of the history of the x-rays' discovery there seems to be absolutely no justification for doubting Röntgen's original merit. It was, of course, not unnatural that Röntgen's masterful interpretation of the effect of an unknown energy source should be envied by those who had reached the threshold

of the discovery but had failed to go beyond. The world gave Röntgen its acclaim and acknowledged his discovery as one of the greatest in many decades. Today, at the semicentennial of radiology, the greatness of his discovery is recognized with gratitude by all those who have derived untold benefits from the roentgen rays in war and peace.

Cleveland Clinic
Cleveland 6, Ohio

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1895  1945

On a New Kind of Rays

WILHELM CONRAD RÖNTGEN

Radiology reprints here translations of Röntgen's original papers on the newly discovered x-rays, appearing in the Sitzungsberichte of the Würzburg Physical Medical Society on Dec. 28, 1895, and March 9, 1896. For these translations (by Arthur Stanton), it is indebted to Science, in which the first was reprinted from Nature on Feb. 14, 1896, and the second, from Electricity (London), on May 15, 1896.

1. A discharge from a large induction coil is passed through a Hittorf's vacuum tube, or through a well-exhausted Crookes' or Lenard's tube. The tube is surrounded by a fairly close-fitting shield of black paper; it is then possible to see, in a completely darkened room, that paper covered on one side with barium platinocyanide lights up with brilliant fluorescence when brought into the neighborhood of the tube, whether the painted side or the other be turned towards the tube. The fluorescence is still visible at two metres distance. It is easy to show that the origin of the fluorescence lies within the vacuum tube.

2. It is seen, therefore, that some agent is capable of penetrating black cardboard which is quite opaque to ultra-violet light, sunlight or arc-light. It is therefore of interest to investigate how far other bodies can be penetrated by the same agent. It is readily shown that all bodies possess this same transparency, but in very varying degrees. For example, paper is very transparent; the fluorescent screen will light up when placed behind a book of a thousand pages; printer's ink offers no marked resistence. Similarly the fluorescence shows behind two packs of cards; a single card does not visibly diminish the brilliancy of the light. So, again, a single thickness of tinfoil hardly casts a shadow on the screen; several have to be superposed to produce a marked effect. Thick blocks of wood are still transparent. Boards of pine two or three centimetres thick absorb only very little. A piece of sheet aluminium, 15 mm. thick, still allowed the X-rays (as I will call the rays, for the sake of brevity) to pass, but greatly reduced the fluorescence. Glass plates of similar thickness behave similarly; lead glass is, however, much more opaque than glass free from lead. Ebonite several centimetres thick is transparent. If the hand be held before the fluorescent screen, the shadow shows the bones darkly, with only faint outlines of the surrounding tissues.

Water and several other fluids are very transparent. Hydrogen is not markedly more permeable than air. Plates of copper, silver, lead, gold and platinum also allow the rays to pass, but only when the metal is thin. Platinum .2 mm. thick allows some rays to pass; silver and copper are more transparent. Lead 1.5 mm. thick is practically opaque. If a square rod of wood 20 mm. in the side be painted on one face with white lead it casts little shadow when it is so turned that the painted face is parallel to the X-rays, but a strong shadow if the rays have to pass through the painted side. The salts of the metal, either solid or in solution, behave generally as the metals themselves.

3. The preceding experiments lead to the conclusion that the density of the bodies is the property whose variation mainly affects their permeability. At least no other property seems so marked in this connection. But that the density alone does not determine the transparency is shown by an experiment wherein plates of similar thickness of Iceland spar, glass, aluminium and quartz were employed as screens. Then the Iceland spar showed itself much less transparent than the other bodies, though of approximately the same density. I have not remarked any strong fluorescence of Iceland spar compared with glass (see below, No. 4).

4. Increasing thickness increases the

132 Sitzungsberichte der physikal.-medicin. Gesellschaft. Jahrg. 1895.

frühere Mitglieder der Gesellschaft lediglich deshalb nicht mehr im Personalverzeichnisse geführt würden, weil sie bei ihrem Weggange aus Würzburg vergessen hatten, den entsprechenden Antrag zu stellen.

Herr von Kölliker stellt deshalb einen Antrag auf diesbezügliche Aenderung der Statuten. — Ueber denselben soll in der ersten Sitzung des nächsten Geschäftsjahres berathen werden.

Am 28. Dezember wurde als Beitrag eingereicht:

W. C. Röntgen: Ueber eine neue Art von Strahlen.

(Vorläufige Mittheilung.)

1. Lässt man durch eine *Hittorf*'sche Vacuumröhre, oder einen genügend evacuirten *Lenard*'schen, *Crookes*'schen oder ähnlichen Apparat die Entladungen eines grösseren *Ruhmkorff*'s gehen und bedeckt die Röhre mit einem ziemlich eng anliegenden Mantel aus dünnem, schwarzem Carton, so sieht man in dem vollständig verdunkelten Zimmer einen in die Nähe des Apparates gebrachten, mit Bariumplatincyanür angestrichenen Papierschirm bei jeder Entladung hell aufleuchten, fluoresciren, gleichgültig ob die angestrichene oder die andere Seite des Schirmes dem Entladungsapparat zugewendet ist. Die Fluorescenz ist noch in 2 m Entfernung vom Apparat bemerkbar.

Man überzeugt sich leicht, dass die Ursache der Fluorescenz vom Entladungsapparat und von keiner anderen Stelle der Leitung ausgeht.

2. Das an dieser Erscheinung zunächst Auffallende ist, dass durch die schwarze Cartonhülse, welche keine sichtbaren oder ultravioletten Strahlen des Sonnen- oder des elektrischen Bogenlichtes durchlässt, ein Agens hindurchgeht, das im Stande ist, lebhafte Fluorescenz zu erzeugen, und man wird deshalb wohl zuerst untersuchen, ob auch andere Körper diese Eigenschaft besitzen.

Man findet bald, dass alle Körper für dasselbe durchlässig sind, aber in sehr verschiedenem Grade. Einige Beispiele führe ich an. Papier ist sehr durchlässig:[1] hinter einem eingebun-

[1] Mit „Durchlässigkeit" eines Korpers bezeichne ich das Verhältniss der Helligkeit eines dicht hinter dem Körper gehaltenen Fluorescenzschirmes zu derjenigen Helligkeit des Schirmes, welcher dieser unter denselben Verhältnissen aber ohne Zwischenschaltung des Korpers zeigt.

Reproduction of the opening paragraphs of Röntgen's first communication on the x-rays, as originally published.

hindrance offered to the rays by all bodies. A picture has been impressed on a photographic plate of a number of superposed layers of tinfoil, like steps, presenting thus a regularly increasing thickness. This is to be submitted to photometric processes when a suitable instrument is available.

5. Pieces of platinum, lead, zinc, and aluminium foil were so arranged as to produce the same weakening of the effect. The annexed table shows the relative thickness and density of the equivalent sheets of metal.

	Thickness	Relative thickness	Density
Platinum	0.018 mm.	1	21.5
Lead	0.050 mm.	3	11.3
Zinc	0.100 mm.	6	7.1
Aluminium	3.500 mm.	200	2.6

From these values it is clear that in no case can we obtain the transparency of a body from the product of its density and thickness. The transparency increases much more rapidly than the product decreases.

6. The fluorescence of barium platinocyanide is not the only noticeable action of the X-rays. It is to be observed that other bodies exhibit fluorescence, *e. g.*, calcium sulphide, uranium glass, Iceland spar, rock salt, etc.

Of special interest in this connection is the fact that photographic dry plates are sensitive to the X-rays. It is thus possible to exhibit the phenomena so as to exclude the danger of error. I have thus confirmed many observations originally made by eye observation with the fluorescent screen. Here the power of the X-rays to pass through wood or cardboard becomes useful. The photographic plate can be exposed to the action without removal of the shutter of the dark slide or other protecting case, so that the experiment need not be conducted in darkness. Manifestly, unexposed plates must not be left in their box near the vacuum tube.

It seems now questionable whether the impression on the plate is a direct effect of the X-rays, or a secondary result induced by the fluorescence of the material of the plate. Films can receive the impression as well as ordinary dry plates.

I have not been able to show experimentally that the X-rays give rise to any calorific effects. These, however, may be assumed, for the phenomena of fluorescence show that the X-rays are capable of transformation. It is also certain that all the X-rays falling on a body do not leave it as such.

The retina of the eye is quite insensitive to these rays; the eye placed close to the apparatus sees nothing. It is clear from the experiments that this is not due to want of permeability on the part of the structures of the eye.

7. After my experiments on the transparency of increasing thicknesses of different media, I proceeded to investigate whether the X-rays could be deflected by a prism. Investigations with water and carbon bisulphide in mica prisms of 30° showed no deviation either on the photographic or the fluorescent plate. For comparison, light rays were allowed to fall on the prism as the apparatus was set up for the experiment. They were deviated 10 mm. and 20 mm. respectively in the case of the two prisms.

With prisms of ebonite and aluminium I have obtained images on the photographic plate which point to a possible deviation. It is, however, uncertain, and at most would point to a refractive index 1.05. No deviation can be observed by means of the fluorescent screen. Investigations with the heavier metals have not as yet led to any result, because of their small transparency and the consequent enfeebling of the transmitted rays.

On account of the importance of the question it is desirable to try in other ways whether the X-rays are susceptible of refraction. Finely-powdered bodies allow in thick layers but little of the incident light to pass through, in consequence of refraction and reflection. In the case of the X-rays, however, such layers of powder are for equal masses of substance equally transparent with the coherent solid itself. Hence

we cannot conclude any regular reflection or refraction of the X-rays. The research was conducted by the aid of finely-powdered rock salt, fine electrolytic silver powder, and zinc dust, already many times employed in chemical work. In all these cases the result, whether by the fluorescent screen or the photographic method, indicated no difference in transparency between the powder and the coherent solid.

It is, hence, obvious that lenses cannot be looked upon as capable of concentrating the X-rays; in effect, both an ebonite and a glass lens of large size prove to be without action. The shadow photograph of a round rod is darker in the middle than at the edge; the image of a cylinder filled with a body more transparent than its walls exhibits the middle brighter than the edge.

8. The preceding experiments, and others which I pass over, point to the rays being incapable of regular reflection. It is, however, well to detail an observation which at first sight seemed to lead to an opposite conclusion.

I exposed a plate, protected by a black paper sheath, to the X-rays, so that the glass side lay next to the vacuum tube. The sensitive film was partly covered with star-shaped pieces of platinum, lead, zinc and aluminium. On the developed negative the star-shaped impression showed dark under platinum, lead, and, more markedly, under zinc; the aluminium gave no image. It seems, therefore, that these three metals can reflect the X-rays; as, however, another explanation is possible, I repeated the experiment with this only difference, that a film of thin aluminium foil was interposed between the sensitive film and the metal stars. Such an aluminium plate is opaque to ultraviolet rays, but transparent to X-rays. In the result the images appeared as before, this pointing still to the existence of reflection at metal surfaces.

If one considers this observation in connection with others, namely, on the transparency of powders, and on the state of the surface not being effective in altering the passage of the x-rays through a body, it leads to the probable conclusion that regular reflection does not exist, but that bodies behave to the X-rays as turbid media to light.

Since I have obtained no evidence of refraction at the surface of different media, it seems probable that the X-rays move with the same velocity in all bodies, and in a medium which penetrates everything, and in which the molecules of bodies are embedded. The molecules obstruct the X-rays the more effectively as the density of the body concerned is greater.

9. It seemed possible that the geometrical arrangement of the molecules might affect the action of a body upon the X-rays, so that, for example, Iceland spar might exhibit different phenomena according to the relation of the surface of the plate to the axis of the crystal. Experiments with quartz and Iceland spar on this point lead to a negative result.

10. It is known that Lenard in his investigations on cathode rays has shown that they belong to the ether and can pass through all bodies. Concerning the X-rays the same may be said.

In his latest work Lenard has investigated the absorption coefficients of various bodies for the cathode rays, including air at atmospheric pressure, which gives 4.10, 3.40, 3.10 for 1 cm., according to the degree of exhaustion of the gas in discharge tube. To judge from nature of the discharge, I have worked at about the same pressure, but occasionally at greater or smaller pressures. I find using a Weber's photometer that the intensity of the fluorescent light varies nearly as the inverse square of the distance between screen and discharge tube. This result is obtained from three very consistent sets of observations at distances of 100 and 200 mm.; hence air absorbs the X-rays much less than the cathode rays. This result is in complete agreement with the previously described result, that the fluorescence of the screen can be still observed at 2 metres from the vacuum tube. In general other bodies behave like air; they are more transparent for the X-rays than for the cathode rays.

11. A further distinction, and a noteworthy one, results from the action of a magnet. I have not succeeded in observing any deviation of the X-rays even in very strong magnetic fields.

The deviation of cathode rays by the magnet is one of their peculiar characteristics; it has been observed by Hertz and Lenard that several kinds of cathode rays exist, which differ by their power of exciting phosphorescence, their susceptibility of absorption and their deviation by the magnet; but a notable deviation has been observed in all cases which have yet been investigated, and I think that such deviation affords a characteristic not to be set aside lightly.

12. As the result of many researches, it appears that the place of most brilliant phosphorescence of the walls of the discharge tube is the chief seat whence the X-rays originate and spread in all directions; that is, the X-rays proceed from the front where cathode rays strike the glass. If one deviates the cathode rays within the tube by means of a magnet, it is seen that the X-rays proceed from a new point, *i. e.*, again from the end of the cathode rays.

Also for this reason the X-rays which are not deflected by a magnet cannot be regarded as cathode rays which have passed through the glass, for that passage cannot, according to Lenard, be the cause of the different deflection of the X-rays. Hence, I concluded that the rays are not identical with the cathode rays, but are produced from the cathode rays at the glass surface of the tube.

13. The rays are generated not only in glass. I have obtained them in an apparatus closed by an aluminium plate 2 mm. thick. I propose later to investigate the behavior of other substances.

14. The justification of the term "rays," applied to the phenomena, lies partly in the regular shadow pictures produced by the interposition of a more or less permeable body between the source and a photographic plate or fluorescent screen.

I have observed and photographed many such shadow pictures. Thus, I have an outline of part of a door covered with lead paint; the image was produced by placing the discharge tube on one side of the door, and the sensitive plate on the other. I have also a shadow of the bones of the hand; of a wire wound upon a bobbin; of a set of weights in a box; of a compass card and needle completely enclosed in a metal case; of a piece of metal where the X-rays show the want of homogeneity, and of other things.

For the rectilinear propagation of the rays I have a pin-hole photograph of the discharge apparatus covered with black paper. It is faint, but unmistakable.

15. I have sought for interference effects of the X-rays, but, possibly in consequence of their small intensity, without result.

16. Researches to investigate whether electrostatic forces act on the X-rays are begun, but not yet concluded.

17. If one asks, what then are these X-rays; since they are not cathode rays, one might suppose, from their power of exciting fluorescence and chemical action, them to be due to ultra-violet light. In opposition to this view a weighty set of considerations presents itself. If X-rays be indeed ultra-violet light, then that light must possess the following properties.

(*a*) It is not refracted in passing from air into water, carbon bisulphide, aluminium, rock salt, glass or zinc.

(*b*) It is incapable of regular reflection at the surfaces of the above bodies.

(*c*) It cannot be polarized by any ordinary polarizing media.

(*d*) The absorption by various bodies must depend chiefly on their density.

That is to say, these ultra-violet rays must behave quite differently from the visible, infra-red, and hitherto known ultra-violet rays.

These things appear so unlikely that I have sought for another hypothesis.

A kind of relationship between the new rays and light rays appears to exist; at least the formation of shadows, fluorescence, and the production of chemical action point in this direction. Now it has

been known for a long time that, besides the transverse vibrations which account for the phenomena of light, it is possible that longitudinal vibrations should exist in the ether, and according to the view of some physicists must exist. It is granted that their existence has not yet been made clear, and their properties are not experimentally demonstrated. Should not the new rays be ascribed to longitudinal waves in the ether?

I must confess that I have in the course of this research made myself more and more familiar with this thought, and venture to put the opinion forward, while I am quite conscious that the hypothesis advanced still requires a more solid foundation.

Second Communication

As my investigations will have to be interrupted for several weeks, I propose in the following paper to communicate a few new results.

§ 18. At the time of my first communication it was known to me that X-rays were able to discharge electrified bodies, and I suspected that it was X-rays, not the unaltered cathode rays, which got through his aluminum window, that Lenard had to do with in connection with distant electrified bodies. When I published my researches, however, I decided to wait until I could communicate unexceptionable results. Such are only obtainable when one makes the observation in a space which is not only completely protected against the electrostatic influences of the vacuum tube, leading-in wires, induction coil, etc., but which is also protected against the air coming from the vicinity of the discharge apparatus. To this end I made a box of soldered sheet zinc large enough to receive me and the necessary apparatus, and which, even to an opening which could be closed by a zinc door, was quite airtight. The wall opposite the door was almost covered with lead. Near one of the discharge apparatus placed outside, the lead-covered zinc wall was provided with a slot 4 cm. wide, and the opening was then hermetically closed with a thin aluminum sheet. Through this window the X-rays could come into the observation box. I have observed the following phenomena:

(*a*) Positively or negatively electrified bodies in air are discharged when placed in the path of X-rays, and the more quickly the more powerful the rays. The intensity of the rays was estimated by their effect on a fluorescent screen or on a photographic plate. It is the same whether the electrified bodies are conductors or insulators. Up to the present I have discovered no specific difference in the behavior of different bodies with regard to the rate of discharge, and the same remark applies to the behavior of positive and negative electricity. Nevertheless, it is not impossible that small differences exist.

(*b*) If an electrical conductor is surrounded by a solid insulator, such as paraffin, instead of by air, the radiation acts as if the insulating envelope were swept by a flame connected to earth.

(*c*) If this insulating envelope is closely surrounded by a conductor connected to earth, which should like the insulator be transparent to X-rays, the radiation, with the means at my disposal, apparently no longer acts on the inner electrified conductor.

(*d*) The observations described in *a*, *b* and *c* tend to show that air traversed by X-rays possesses the property of discharging electrified bodies with which it comes in contact.

(*e*) If this be really the case, and if, further, the air retains this property for some time after the X-rays have been extinguished, it must be possible to discharge electrified bodies by such air, although the bodies themselves are not in the path of the rays.

It is possible to convince oneself in various ways that this actually happens. I will describe one arrangement, perhaps not the simplest possible. I employed a brass tube 3 cm. in diameter and 45 cm. long. A few centimeters from one end a portion of the tube was cut away and replaced by a thin sheet of aluminum. At the other end an insulated brass ball fastened to a metal rod was led into the tube through an air-tight gland. Between the ball and the closed end of the tube a side tube was soldered on, which could be placed in communication with an aspirator. When the aspirator was worked the brass ball was surrounded by air, which on its way through the tube went past the aluminum window. The distance from the window to the ball was over 20 cm. I arranged the tube in the zinc box in such a manner that the X-rays passed through the aluminum window at right angles to the axis of the tube, so that the insulated ball was beyond the reach of the rays in the shadow. The tube and the zinc box were connected together; the ball was connected to a Hankel electroscope. It was seen that a charge (positive or negative) communicated to the ball was not affected by the X-rays so long as the air in the tube was at rest, but that the charge immediately diminished considerably when the aspirator caused the air traversed by the rays to stream past the ball. If the ball by being connected to accumulators was kept at a constant potential, and if air which had been traversed by the rays was sucked through the tube, an electric current was started as if the ball had been connected with the wall of the tube by a bad conductor.

(*f*) It may be asked in what way the air loses this property communicated to it by the X-rays. Whether it loses it as time goes on, without coming into contact with other bodies, is still doubtful. It is quite certain, on the other hand, that a short disturbance of the air by a body of large surface, which need not be electrified, can render the air inoperative. If one pushes, for example, a sufficiently thick plug of cotton wool so far into the tube that the air which has been traversed by the rays must stream through the cotton wool before it reaches the ball, the charge of the ball remains unchanged when suction is commenced. If the plug is placed exactly in front of the aluminum window the result is the same as if there were no cotton wool, a proof that dust particles are not the cause of the observed discharge. Wire gauze acts in the same way as cotton wool, but the meshes must be very small and several layers must be placed one over the other if we want the air to be active. If the nets are not connected to earth, as heretofore, but connected to a constant-potential source of electricity, I have always observed what I expected; however, these investigations are not concluded.

(*g*) If the electrified bodies are placed in dry hydrogen instead of air they are equally well discharged. The discharge in hydrogen seems to me somewhat slower. This observation is not, however, very reliable, on account of the difficulty of securing equally powerful X-rays in successive experiments. The method of filling the apparatus with hydrogen precluded the possibility of the thin layer of air which clings to the surface of the bodies at the commencement playing an appreciable part in connection with the discharge.

(*h*) In highly-exhausted vessels the discharge of a body in the path of the X-rays takes place far more slowly—in one case it was, for instance, 70 times more slowly—than in the same vessels when filled with air or hydrogen at atmospheric pressure.

(*i*) Experiments on the behavior of a mixture of chlorine and hydrogen, when under the influence of the X-rays, have been commenced.

(*j*) Finally, I should like to mention that the results of the investigations on the discharging property of the X-rays, in which the influence of the surrounding gases was not taken into account, should be for the most part accepted with reserve.

§ 19. In many cases it is of advantage to put in circuit between the X-ray producer and the Ruhmkorff coil a Tesla condenser and transformer. This arrange-

ment has the following advantages: Firstly, the discharge apparatus gets less hot, and there is less probability of its being pierced; secondly, the vacuum lasts longer, at least this was the case with my apparatus; and thirdly, the apparatus produces stronger X-rays. In apparatus which was either not sufficiently or too highly exhausted to allow the Ruhmkorff coil alone to work well, the use of a Tesla transformer was of great advantage.

The question now arises—and I may be permitted to mention it here, though I am at present not in a position to answer it—whether it be possible to generate X-rays by means of a continuous discharge at a constant discharge potential, or whether oscillations of the potential are invariably necessary for their production.

§ 20. In § 13 of my first communication it was stated that X-rays not only originate in glass, but also in aluminum. Continuing my researches in this direction, I have found no solid bodies incapable of generating X-rays under the influence of cathode rays. I know of no reason why liquids and gases should not behave in the same way.

Quantitative differences in the behavior of different bodies have, however, revealed themselves. If, for example, we let the cathode rays fall on a plate, one-half consisting of a 0.3 mm. sheet of platinum and the other half of a 1 mm. sheet of aluminum, a pin-hole photograph of this double plate will show that the sheet of platinum emits a far greater number of X-rays than does the aluminum sheet, this remark applying in either case to the side upon which the cathode rays impinge. From the reverse side of the platinum, however, practically no X-rays are emitted, but from the reverse side of the aluminum a relatively large number are radiated. It is easy to construct an explanation of this observation; still it is to be recommended that before so doing we should learn a little more about the characteristics of X-rays.

It must be mentioned, however, that this fact has a practical bearing. Judging by my experience up to now, platinum is the best for generating the most powerful X-rays. I used a few weeks ago, with excellent results, a discharge apparatus in which a concave mirror of aluminum acted as cathode and a sheet of platinum as anode, the platinum being at an angle of 45 deg. to the axis of the mirror and at the center of curvature.

§ 21. The X-rays in this apparatus start from the anode. I conclude from experiments with variously-shaped apparatus that as regards the intensity of the X-rays it is a matter of indifference whether or not the spot at which these rays are generated be the anode. With a special view to researches with alternate currents from a Tesla transformer, a discharge apparatus is being made in which both electrodes are concave aluminum mirrors, their axes being at right angles; at the common center of curvature there is a "cathode-ray catching" sheet of platinum. As to the utility of this apparatus I will report at a later date.

EDITORIAL

A New Kind of Rays

(Reprinted from the Editorial Page of the J. A. M. A., Feb. 15, 1896)

The general interest in the recent discovery of Prof. Röntgen, the details of which now fill the daily press and which were at first received with incredulity by the public as probably a scientific hoax, seems to call for some notice. . .

In regard to the scientific question as to whether the results obtained by experimenters are due to the previously recognized cathode rays or to a new form of radiation as Prof. Röntgen suggests we can, of course, express no opinion; it is a matter to be decided by physicists. The fact that we have, however, a force, for that is what it may be called, that will act on the sensitive chemicals of the photographic plate through flesh, cartilage, skin, and other tissues of the animal body, is enough to be fertile of practical suggestions to any thinking physician or surgeon. The further fact that these rays go directly through prisms and lenses without modification or change of course adds to their possibilities in a medical point of view; it insures the accuracy of the image from distortion by refractive power of the different solids and fluids of the body. The further fact that in a general way only the density of the medium penetrated seems to affect them is suggestive of practical medical and surgical possibilities; it hints at future valuable physiologic revelations as well as diagnostic aids. It is only a hint, however, and whether it is to be ever realized to any extent is perhaps open to serious question. As regards its therapeutic possibilities which have already become the plaything of the popular imagination, they may be left to future investigation; they are not in a stage as yet for medical opinions to pass on the question of even their existence. There will doubtless be an extensive advertisement of cathode ray baths, x-ray treatments, etc., but it is to be hoped that any active exploitations of these will, until the matter is more elucidated by accurate scientific researches, be confined to the irregulars who have no standing in the regular medical profession.

The real utility of the discovery has so far been demonstrated to a limited extent in the field of surgery. A few accounts have appeared in the lay press of needles, bullets, etc., having been detected lodged in the tissues, and some light has been thrown on pathologic diagnosis in one or two cases. In France, M. Lannelongue believes he has been able to show by this method that in a femur affected with osteomyelitis the destruction of bone progresses from the center to the periphery rather than in the opposite direction as had been previously held. When it is considered that the discovery is as yet only a few weeks old, and that students all over the civilized world are laboring to investigate it and to perfect the methods of its application, it may not be unreasonable to hope for much more important results in the near or remote future. At present, however, the limitations of the methods are too great and the medical nature of the discovery is, as yet, a largely unknown quantity. Its surgical utility in certain ways has probably been sufficiently indicated by what has been already done, but enthusiasm as to its future should be tempered by a scientific spirit of moderation that proves all things before building its faith upon them.

After Fifty Years

"It is only a hint. . . ." The skepticism with which Röntgen's epochal communication, "On A New Kind of Rays," was received finds expression in these words from the editorial reprinted on the opposite page, the first official recognition, by the *Journal of the American Medical Association*, of what has proved to be one of the most important scientific achievements of the past century. Today it seems inconceivable that, in spite of the meager reports then at hand, the benefits which were destined to accrue to humanity from this discovery were not more clearly envisioned.

Fortunately, there were those by whom the possibilities, however vague, were accepted as a challenge. Step by step, on the basis of scientific research, this intrepid group proceeded to improve the crude equipment at first available, to devise new technics, to unearth the hidden disease processes of the body, to venture into new fields of application. These developments are traced in greater detail in the following pages. But those men of vision, who accomplished so much with so little, paid a price for their achievements in suffering and even death—the late effects of the then inadequately known rays. It is to the memory of those early pioneers, as well as to Röntgen, that this issue of RADIOLOGY is dedicated.

Many fields were to feel the impact of Röntgen's discovery. In the science of physics radical changes were to stem from it. The development of spectrometry by Bragg not only made possible studies of the atomic structure of recognized crystals but showed that many organic substances, as silk and rubber, are basically crystalline. Industry profited by the radiographic examination of structural materials, and the rays which Röntgen had demonstrated in the peace of his laboratory became an asset in time of war for testing the integrity of castings and other strategic materials. Already radical changes in our mode of living have grown out of the application of electronic principles, and the future promises still more revolutionary developments.

In the field of medicine, roentgenology has advanced during the past fifty years from feeble beginnings to take its place among the most respected specialties. At first it was devoted largely to the detection of foreign bodies and changes in the osseous system, but as early as June 1896 one observer was able to reveal a concretion in the kidney. Other pioneers were soon demonstrating lesions elsewhere in the body, proving to a startled medical world that it had at its disposal not merely a scientific curiosity but an agent capable of making visually perceptive, in the living, many anatomic, physiologic, and pathologic processes which had hitherto been demonstrable only at autopsy, or at best on the operating table.

During the same early period biologic reactions, as an irritation of the eyes and a persistent dermatitis of the hands, led certain workers to speculate upon the therapeutic possibilities of the new discovery. It is true that the feeble emission of rays obtainable with the tubes then available had but a minimal effect, but as more efficient apparatus was developed and new knowledge of the properties of the rays was acquired, their therapeutic effectiveness became increasingly apparent and their binary character was established.

To Wilhelm Conrad Röntgen full credit must be given for the genius which led him to recognize a hitherto unknown form of radiation, but for its full development roentgenology has been dependent upon the sustained effort and collaboration of many scientists in many lands. It demonstrates again the truth that science is universal, without limitations of nationality or race.

Development of Diagnostic X-Ray Apparatus During the First Fifty Years

PAUL C. HODGES, M.D.

Division of Roentgenology, The University of Chicago

INTERNAL MEDICINE, surgery, and the clinical specialties have availed themselves of the fruits of the physical and chemical age to such an extent that the modern internist would be handicapped severely if he were deprived of his thermometer, sphygmomanometer, electrocardiograph, and sulfonamides, while the surgeon would sorely miss local anesthetics and the myriad appointments of the present-day operating room, but our colleagues' dependence on physics, chemistry, and engineering is as nothing compared with ours. While it is true that we radiologists are useful in proportion to our excellence as physicians and that it is our clinical education and experience that count most, still we are powerless to bring those attributes into play until we have first made good-quality roentgenograms, produced a good fluoroscopic image, or generated a beam of therapeutic rays of precisely known quality, quantity, and dimension. As a result of our great dependence on apparatus and technic, it is only natural that these matters have occupied a large place in our attention and required the expenditure of a great deal of our time.

As late as the close of the nineteenth century, our ablest surgeons and the departments of surgery in our leading universities deemed it proper and, in fact, mandatory that they devote a considerable portion of their attention to the devising of new instruments and new operative procedures, but in recent years such pursuits have come to be considered unworthy. By false analogy, some critics have contended that radiologists should now leave all of their technical problems to the engineering staffs of the commercial manufacturers. It seems safe to assume that eventually our radiological tools will reach such a degree of perfection and standardization as to allow us to ignore the details of their construction and operation, devoting ourselves exclusively to the medical phases of our work, but that day is not yet here.

Our interest in technical matters has not remained static, however, but has shifted with the years, and as certain parts of our equipment have approached perfection we have been quite as willing as our surgical colleagues to drop consideration of those parts in order to conserve time and effort for clinical work. This shift in interest may have been scarcely discernible to those who were experiencing it, but as one looks back over the half century and for convenience breaks down the period into five decades, a fairly definite pattern becomes visible.

FIRST DECADE

By the close of the first decade (1905), almost every part of the body had been studied more or less successfully, but the principal clinical use of x-rays was for the care of fractures and dislocations and the detection of foreign bodies, and even in these fields the use was extremely limited. X-ray tubes were still primitive in design and fickle in performance, and intensifying screens were of a quality that deserved and received little consideration.

The small laboratory type induction coil operating on storage batteries and provided with a mechanical interrupter had given way, in this country at least, to the static machine which, in turn, was now in the process of being displaced by more powerful induction coils supplied from power lines and provided with electrolytic or mercury jet interrupters.

SECOND DECADE

The next ten years saw an enormous spread in clinical roentgenology, and by

the close of the second decade (1915) physicians generally employed x-rays, or at least wished that they might be able to employ them, in the examination of the chest and the alimentary tract, as well as for all of the injuries and diseases of the skeletal system. On the technical side, the so-called interrupterless transformer had about displaced induction coils, and the recently introduced Coolidge tube was shortly to bring complete obsolescence to that temperamental prima donna, the gas tube.

The importance of the technical changes of that second decade can scarcely be appreciated by one who did not work at radiology during that period. At their best, induction coils had been a terrible nuisance and it seemed at times as though gas tubes had been invented for the specific purpose of trying men's souls. The induction coil required direct current power in an amount not conveniently provided by storage batteries, and in those American communities where the only available power was alternating current this meant that one must provide either a large, expensive motor generator set or a temperamental and inefficient electrolytic rectifier.

The Electrolytic Rectifier: This consisted of a pair of metal-plate electrodes immersed in an alkaline electrolyte, such as ammonium phosphate, sodium bicarbonate, or sodium and potassium tartrate. The positive electrode was made of aluminum, the negative usually of steel, and plates and electrolyte were contained in a glass or porcelain jar partially immersed in the water of a cooling bath.

The aluminum plate was either "formed" by the manufacturer or was "formed" on the job by passing a low current through the cell for a few minutes. By "forming" was meant the deposition on the aluminum of a thin white coating of aluminum salt which polarized the electrode, allowing negative electricity to flow freely through the electrolyte from the indifferent electrode to the aluminum, but opposing a flow in the opposite direction. Four cells were employed, connected so that full-wave rectification was accomplished.

Under the best of operating conditions, electrolytic rectifiers were a poor expedient and the conditions were seldom good. Usually rectifiers were neglected, water that evaporated from electrolyte and cooling bath was not replenished, metal parts were allowed to corrode, and efficiency fell to a low level.

Early Forms of High-Voltage Rectifier: When the induction coil was well designed, the current supply unidirectional, and the interrupter of good design, the high-voltage current produced by the secondary of the coil was approximately unidirectional. Under practical operating conditions, however, the amount of inverse current might be considerable and, inasmuch as inverse current was deleterious to x-ray tubes, considerable effort was expended to suppress it. One of the devices used for this purpose was the so-called Lodge valve tube, which consisted of a pear-shaped vacuum tube provided with a cathode and an anode. The cathode was a large, coiled, aluminum rod that filled the body of the tube; the anode a small disk of steel or other metal located well back in a narrowed arm of the tube. As in all gas tubes, so in this one, the electrons that were essential to conduction were emitted from the cathode as a result of bombardment by positive particles. The anode, by virtue of its smallness and protected location, was bombarded by few positive particles during the phase that it was at negative potential and, because of its physical composition, emitted few electrons for each impact. The cathode, on the contrary, was richly bombarded by positive particles and, being aluminum, gave out copious electrons for each impact. When one or several Lodge tubes were connected in series with the x-ray tube, the useful current of the induction coil passed through the system without much attenuation, while the inverse current was largely suppressed. Similar gas valves were used by Hutton in his early attempts at the rectification of the output of A.C. transformers, but it was not until many years later that hot-cathode valves made such circuits practical.

The Electrolytic Interrupter: The Wehnelt interrupter, as used in this country, usually consisted of a platinum-rod positive electrode, a lead negative electrode, and an electrolyte of 20 per cent sulfuric acid. These electrodes were mounted in a glass or porcelain jar containing 20 per cent sulfuric acid, the jar, in turn, being partially immersed in a cooling water bath. Three such cells were commonly used, one having a large point, one a small point, and one a point of intermediate size. The platinum points protruded through the tips of porcelain candles, the amount of protrusion being controlled by a hand-operated screw, and a series of knife switches made it possible to employ any one or any combination of the points. Interruption was accomplished by the alternate formation and collapse of an insulating coating of gas bubbles about the exposed platinum tip.

Before making a plate, the operator tinkered with the rheostat and the interrupter points until the tube "backed up a five-inch spark" (*i.e.*, operated at 85,000 volts peak) and seemed to be drawing about the proper amount of current. He estimated current by the sound of the interrupter and the intensity and distribution of the apple-green fluorescence which was characteristic of gas tubes.

Exposing more platinum in the interrupter increased the current that could flow through it and decreased the rate of the interruptions, but there was no provision for measuring the rate of interruptions, and the ammeter that usually was connected in series with the primary of the induction coil gave little indication of the amount of x-ray that was being produced by the tube.

Since the one variable that could be controlled was development, it was the skill and diligence of the darkroom worker that determined the quality of the x-ray plates. Not much attention was paid to the strength or temperature of the solutions. The plates were developed one by one in trays under constant visual control and were transferred to the hypo at the exact moment when the technician's practised eye detected, by means of the red light, that the image had "struck through to the back of the plate."

Mercury Interrupters: Motor-driven mercury interrupters were fairly satisfactory if a condenser was connected across the break, and particularly when the dielectric was gas. It was more common, however, to use kerosene and, after being used for a few hours, mercury and kerosene became blended into a sort of mercury ointment.

It was during this second decade that I spent a morning watching one of our ablest American radiologists conducting gastrointestinal examinations. The list was enormous—ten patients in one morning—and I marveled at the fact that he had almost completed the last examination before the mercury interrupter, which was mounted on a shelf on the wall, broke down and had to be overhauled by the engineer. I have great admiration and respect for that radiologist, but when he told me that there were some mornings when he did as many as twelve examinations without a breakdown of the interrupter, though I did not openly question his veracity, still I mentally concluded that enthusiasm for his calling had somewhat clouded his respect for the absolute truth.

Mechanical Rectifier: Those fortunate few whose hospitals and offices were provided with direct current power were spared the inequities of the electrolytic rectifier, but all users of induction coils were faced with the challenge of the interrupter, and everyone recognized that the challenge was not adequately met. It was small wonder, therefore, that when Snook introduced the combination of the closed-core A.C. transformer with a motor-driven centrifugal switch or rectifier, radiologists, instead of calling it by the straightforward name "mechanical rectifier," hailed the machine as the interrupterless transformer. It did away with that abomination, the interrupter, and in their eyes that was what counted most. With this change, the tables were reversed in the matter of A.C. *versus* D.C. power supply. Now the

radiologist who had A.C. power was the fortunate fellow because his mechanical rectifier could be driven by a small, practically trouble-free, synchronous motor, the transformer drawing its power directly from the line, whereas in D.C. installations a rather heavy, somewhat expensive, synchronous converter or so-called rotary converter drove the rectifying switch and also supplied alternating current for the x-ray transformer. The commutator and brushes of the converter required far more attention than the simple slip rings of the synchronous motor, but much more important was the disadvantage that for a converter of reasonable size and cost the power that could be supplied to the transformer was relatively small. Later, as self-rectification brought in small portable and bedside units, the user of D.C. power was put to the cost and inconvenience of providing for each of them a small but none the less heavy and rather expensive synchronous converter to change D.C. to A.C. This advantage of A.C. over D.C. has continued throughout the decades that have followed.

THIRD DECADE

The third decade, which closed in 1925, was unusually fruitful, both clinically and technically. In this period chest films came to be considered indispensable in the handling of pulmonary disease, pyelograms began to occupy a similar position of importance in urology, and at least in the larger centers it became all but unethical to attempt to manage diseases of the gastro-intestinal tract without the aid of x-rays. Cholecystography was introduced, and cardiologists began to be interested in the application of x-rays to their work although, of course, they had been used to some extent in cardiology from the very earliest years, particularly among the French.

Early in the decade the radiator-type Coolidge tube had sponsored self-rectification for small portable bedside and fluoroscopic units.

Double-disk mechanical rectification made it possible to bring the milliammeter down out of the high-tension system and mount it on the control board, closed-core transformers and autotransformer controls were in general use, and time-switches were greatly improved. Double-coated films and double-intensifying screens proved to be an enormous improvement over plates and single screens and, most important of all, Potter's recently invented moving grid opened the way at last to adequate raying of the skull, trunk, and pelvis.

Potter Grid: The importance of Potter's work was recognized and warmly acclaimed by contemporary American radiologists, but the excessive modesty and self-abnegation of Potter's original papers have tended to blind the younger generation to the enormous debt they owe to him. Before Potter, good films of the skull, hip, and other thick parts could be obtained only by the expedient of narrowing the incident beam to small diameter. Full-sized films of the skull, abdomen, and pelvis we owe directly to him.

Bucky, it is true, had laid the ground work by learning from the physicists their concept of the scattering of x-rays and teaching that concept to radiologists. Prior to this we had understood fairly well the phenomena of absorption, transmission, and characteristic emission, but most of us owe to Bucky our appreciation of the fact that some of the radiation impressed upon the surface of the patient's body is scattered out of its straight-line course with resulting blurring of the x-ray image. Scattering is greatest when the voltage is high, the mass of tissue large, and the incident beam broad, so it can be reduced in amount by lowering the voltage, coning the beam, and compressing the part. Bucky taught us that most of the scattered radiation that was formed could be prevented from reaching the film by interposing between patient and film a honeycomb-like metal member that he termed a diaphragm. The interstices of Bucky's diaphragm were, in fact, little metal tubes oriented so that their bores were parallel with the radii of

the spherical angle formed by the incident radiation. Unscattered incident radiation passing through the patient's body passed on through Bucky's diaphragm to reach the film, but the scattered radiation, since it deviated from the radii of the sphere, suffered absorption in the walls of the metal tubes. Bucky's theory was sound as far as it went, but it did not go far enough and the films that he made were practically useless because of the overlying pattern of the diaphragm. By that partially developed theory, since the radiation had a spherical distribution, the suppressor had to be in the form of a segment of a sphere and, therefore, no motion that could be devised for it would wipe out its image. Here Bucky stopped and here the matter stood until Potter attacked the problem in 1913.

I don't know whether Potter theorized, "Since we can't deal with a sphere of radiation, suppose we see what happens if we assume a cylindrical rather than a spherical distribution." Perhaps he just experimented and built his theory as he went along but, in any event, by 1917 he had the answer and, since grids became commercially available in the early twenties, that answer has been at work in x-ray laboratories all over the world. Potter's answer was something like this: "The suppressor doesn't have to be a system of tubes arranged as a segment of a sphere. It works almost exactly as well if it is a series of strips arranged as a segment of a cylinder and, unlike Bucky's spherical diaphragm made up of tubes, a cylindrical grid, composed of strips, casts on the film no image of itself provided it is in uniform motion while the exposure is being made."

I have said that contemporary American radiologists appreciated the importance of Potter's work, but the Europeans of that day appreciated it, too. When I visited German and Austrian universities in the spring of 1923, the most common question that was put to me by their radiologists was: "How may we obtain one of Potter's grids?"

There have been developments with the years, of course. The grid, originally curved, has been made flat; for certain applications it need not move at all and, when it does move, the modern trend is to drive it continuously by means of a reciprocator instead of starting it and stopping it for each exposure, but these are mere variations on Potter's original theme. Let us give credit to Bucky for posing the problem, but particularly to Potter, the fellow who solved it after it had been posed.

FOURTH DECADE

By 1935, which marked the close of the fourth decade, radiology was generally recognized as a legitimate and independent member of the group of medical specialties, with its own body of technical and clinical knowledge, its own facilities for advancing and transmitting that knowledge, its own journals, societies, and examining boards. Most of the tissues of the body and most of the diseases to which those tissues are heir were now regularly subjected to x-ray examination. In particular, this decade had seen the inclusion of the central nervous system, the vascular system, and the genital system among those parts of the body for which x-ray examination had become an almost invariable part of the routine. Technical advances had continued throughout this decade also.

Valve-Tube Rectification: Rectification by means of hot-cathode valve tubes had almost completely displaced mechanical rectification. At first valve tubes were expensive and erratic, and the attempt to economize by using only a single valve brought nothing but trouble and was soon abandoned. However, with the development of small, oil-immersed, four-valve sets, it seemed that at last stability may have been reached in the development of the high-voltage generator.

Shock-Proof Tubes: The shock-proofing of tubes passed from an experimental to a thoroughly practical stage; the rotating anode tube, long known in principle, had reached a degree of ruggedness and was beginning to approach a price which would

allow its wider employment, and the filming fluoroscope began to appear in the catalogues of most of the manufacturers. Planigraphy and the thrice-resuscitated x-ray kymography were creating something of a flurry but were destined to be retired to a place of minor importance, and condenser discharge machines and three-phase generators, after a brief and limited popularity, had entered a decline.

FIFTH DECADE

It is, of course, too soon to evaluate the lasting work of the fifth decade, whose close we are now celebrating, but on the technical side two accomplishments at least seem likely to survive. The first is the perfection of *microfilming* and its adaptation to mass radiography of the chest. As in so many other phases of x-ray work, the concept of microfilming is almost as old as x-rays themselves but the harnessing of the idea and the breaking of it to practical, effective, wide-scale use have come only in very recent years. At the moment the method is practical only for examination of the chest, and serious technical obstacles will have to be overcome before it can be extended to all parts of the body, but there is little reason to doubt that these obstacles will be surmounted within the decade we are about to enter.

Photoelectric Timers: Another accomplishment of the fifth decade is photoelectric timing. As this article is being written, timers for microfilming are in commercial production and presumably will be in wide-scale use during the demobilization of our Armed Forces. Photoelectric timers for general radiography are still in the experimental stage, but there is every reason to believe that they, too, will become commercially available within a very few years.

CLINICAL ASPECTS

On the clinical side there is not the slightest justification for feeling that we may rest upon our laurels. It is true that every system, almost every tissue, and a vast number of the diseases have now been and are being studied by x-ray, and that a great deal of information about them has been collected, but there is scarcely a phase of this work that could not be done better than we now do it. It will be many years, indeed, before students considering radiology as a life's work will be justified in turning from it to something else for the reason that all the discoveries have been made and nothing remains to be done. Actually, the amount of work remaining to be done is prodigious and, in addition to improvement and extension of the body of radiological knowledge, we are faced with the pressing job of making available to the population at large that amount of radiological skill that has already been developed.

SOCIAL ASPECTS

Even in the cities good-quality radiology is available to only a fraction of the population, and outside of the cities the situation is appalling. It will require the expenditure of much thought and energy to rectify the situation and at the same time not interfere with the orderly development of our specialty. Certainly there are two extremes that should be avoided. On the one hand, radiology should not be pauperized to the point where able young physicians no longer care to enter it and, on the other hand, we must oppose all efforts within our ranks to perpetuate the economy of scarcity which in the past made it possible for an inadequate number of radiologists to earn large incomes by caring for a comparatively few patients. There may be a few unscrupulous lay administrators who see only good in the reduction of the radiologist to the role of a subservient, underpaid employee, but the majority of clinic and hospital administrators hold no such views. On the other hand, though there may be a few unenlightened radiologists who favor trade-union tactics for the retaining and improving of advantages now possessed by us, most of our colleagues have no sympathy with such views. But though we ignore extremists on both sides and assume that the majority of radiologists and administrators have the same ends in view,

it does not follow that their task will be easy or immediately successful. The guiding principles are clear, however, and if we will keep them constantly in view, the details can be worked out.

Methods of economizing on time and material must be sought and, when found, adopted. Expensive, time-consuming routines which have only the merit of usage but serve no useful purpose must be abandoned, and, wherever possible, the patient-doctor ratio must be increased. Of course, such practices can be abused with the result that the radiologist is overworked or is made to do shoddy work, but abuses benefit no one and must be avoided.

In the decade that lies ahead, we radiologists should be out in the lead of our profession, exploring the path that medicine should follow in adapting itself to the changed economy that is bound to affect every phase of our national life, since some of the problems are not as new to us as they are to our colleagues in other branches of medical practice.

Undoubtedly much radiology will be supplied at federal expense to the millions of new war veterans. It should be our aim to assist that work in every way and by counsel and example to mold public and official opinion to the idea that the government will have to employ first-quality radiologists if first-quality work is to be expected. Industry, municipalities, and similar agencies presumably will increase the amount of radiology made available to groups for whom they are responsible, and our co-operation here should be the same as in the case of the veterans. And what of private practice? I, for one, have no fear that a people who have just victoriously concluded a war for the preservation of the American way of life will now wish to destroy that way.

Those attributes of private practice which suffer by comparison with the quality of radiology that will be practised in the Veterans Administration and in various types of partially or wholly subsidized clinics will and should fail and disappear. On the other hand, a vigorous, excellent, though perhaps somewhat smaller program of private American radiology will be welcomed not only by that fraction of the population that can afford its somewhat higher fees and more personalized service but also by the nation as a whole, as a standard-setting agency for government hospitals and reduced-rate clinics. In the long run, the public does a surprisingly good job in evaluating the quality as well as the cost of the medical care it receives. It will not indefinitely pay higher fees for the subtle advantages of being cared for in a private office unless the medical quality of the care received is at least as good as that available in low-cost clinics and, on the other hand, will not be content to reap the financial advantage of the clinic unless it is convinced that the quality of its work is good.

PROBLEMS FOR THE FUTURE

Even if I were inclined to fancy myself a prophet, still I would abstain from radiologic prophecy lest I survive for a few more years to experience the embarrassment of the eminent Philadelphia physician who, shortly after the discovery of x-rays, predicted that x-ray apparatus was so expensive and its employment so time-consuming that it could never come into general clinical use, or that of my Chicago colleague who, a number of years ago, concluded that x-ray apparatus had reached a final state of perfection except possibly for some simplification of design. But it is not an act of prophecy to point out radiological chores that need doing and to express the hope that in the years ahead someone may attend to them.

Better Films: Silver halide suspended in water-soluble gelatin always has been and perhaps always must be the only really feasible photographic medium, but our work would benefit if it ever became possible to incorporate the active photographic agent in the base itself, with the complete abandonment of a surface emulsion and the substitution of gases or chemicals dissolved in volatile solvents for the aqueous processing solutions that are now employed. Such

films—possibly quite incapable of attainment—might be expected to be vastly more durable than those in use today and their processing might be much more rapid.

Better Screens: The screen situation is ripe for change, and with the widened chemical interest in fluorescent materials for lamps, paints, television tubes, etc., change may well be expected. Already speed and definition have reached a respectable degree of excellence, but cost and lack of durability are still excessive. No one expects a white shirt to last more than one summer day without a trip to the laundry, and the garter manufacturers urge that their product be looked upon as expendable and rather short-lived, but we have been educated to believe that it is logical for expensive, fragile, white intensifying screens to make thousands of trips to the loading bench before they have paid their way and can be discarded. Present-day screens may be washed, it is true, but not very often and not very successfully and, even when every feasible precaution is taken, deterioration is rapid. Those of us who periodically scoop the treasury to install new screens in all our cassettes know only too well the difference between the excellent quality of films that can be produced when screens are new and the shabby appearance of those made only a few weeks later when deterioration has begun.

Two obvious remedies are at hand—one still entirely neglected, the other now being worked at. The first is a "clean towel service" for screens. It should be possible to contract for screens by the year, the representative of the manufacturer to replace screens as soon as defects develop, perhaps with some additional insurance premium to cover those damaged by accident or carelessness rather than by normal wear and tear. This suggestion is based on the knowledge that the materials used in the making of a screen cost a microscopic fraction of its selling price and the assumption that that price largely represents, therefore, the labor and overhead of manufacture and distribution. Many more screens would be required under my plan, and somewhat more labor would have to be expended, but the real cost of such a service might be surprisingly little more than that of the present system, which is so extremely unsatisfactory. The other remedy is the provision of a tough abrasion-resisting surface coating that really will stand washing, and that matter, I am glad to say, is now receiving the attention of screen manufacturers.

Better Cassettes: Cassettes have become better in recent years, but they still need improvement. In anticipation of phototiming, the backs should be made of standard-thickness aluminum without lead and with at least the central area free of springs or rivets. Frames should be made of steel of a quality that combines, as far as possible, maximum lightness and toughness with maximum resistance to rust. Better means should be sought for the mounting of screens, and the front of the cassette should be provided with a flush marker which will photograph onto the film the serial number of the cassette and the name or initials of the hospital, clinic, or individual radiologist. The serial number should appear, also, on the back of the cassette, so that when films show defects that are caused by faults in screens or cassettes the faulty cassette may easily be located and removed from service.

Better Tubes: Our gratitude for the excellence of the x-ray tubes available in this, the fiftieth year following the discovery of x-rays, should not blind us to the need of still further improvement. Having myself experimented since the early twenties with the forced circulation of the insulating oil used with diagnostic x-ray tubes, I am convinced that oil circulation and forced cooling of the oil are important. They are employed now by one manufacturer, but the practice should become general and, if there are valid patents restricting such general use, some program should be worked out for the granting of licenses under those patents.

With the years, rotating anode tubes have become smaller, longer-lived, quieter, and somewhat less expensive, though

there is ample room for improvement along all these lines; but their cooling remains a serious problem, particularly when one wishes to employ them in the filming fluoroscope. Long ago Coolidge patented and then abandoned a tube in which not merely the anode but the entire tube rotated, a magnetic field operating through the glass to deflect the cathode stream so that the focal point was held fixed in space while the spinning mushroom-shaped target rotated beneath it. Modern, short, cylindrical tubes are much better adapted to such a system than were the long, globular tubes of thirty years ago, and in the intervening years much has been learned about the focusing of electrons by combinations of electric and magnetic fields. The bearings of such a rotating tube would be oil-immersed ball bearings of standard design and, therefore, extremely quiet and practically imperishable, and the rotation of the tube within the oil housing could be made to provide vigorous circulation of the oil. If a good blower were added, a tube of this sort should excel all others in its ability to eliminate the heat generated in the target and thus be superior to others for all phases of diagnostic x-ray work, and particularly for use in the filming fluoroscope.

Dr. Coolidge's company would be the logical people to undertake a modern development of his old idea, but if they are not interested, others perhaps may be induced to take up the matter, for the patent has long since expired and the field is open to anyone.

Film Processing: Our record of achievement in the processing of x-ray film is nothing to brag about. Beginning with Robert Kelley's little motor-driven teeter-totter for rocking trays, we have improved a little on the darkroom methods we inherited from the daguerreotypers, but not much. Our constant temperature devices seldom are accurate; facilities for preparing, handling, and changing solutions are primitive; wash tanks and driers, though better than they were ten years ago, still are far from satisfactory. While we have been putting up with our archaic methods, moving picture processors, military Air Force photographers, and industrial x-ray engineers have made great strides in automatic processing and, now that the war has ended, some of the manufacturers who have been thus employed are seriously at work adapting their product to the quite different conditions of clinical radiology. It is high time that they have begun to do so because with the growth of phototiming, the automatic development of clinical x-ray films becomes increasingly important.

The ideal installation of the future will be a stainless steel unit that receives exposed film at one end and delivers dried film at the other, with a minimum lapse of time and with provision for the temporary removal of emergency films as soon as fixation is completed. Processing solutions will be continuously replenished, either by gravity or by means of pumps, and these solutions will be conducted through large stainless steel tubes having a minimum of pipe fittings. The solution lines will pass through strainers of ample size and of a design that allows easy, rapid, daily cleaning, and there will be precise and rugged machinery for maintaining temperature at the desired point. Finally, such an ideal installation will include a simple but well constructed phototube densitometer for the daily reading of test strips. Even now automatic developing is employed in a few x-ray laboratories, but the practice should become general and the apparatus required for it should be standardized rather than custom-built for each installation.

Film Handling: When the x-ray team consists of one physician and a single helper who loads the cassettes, operates the machine, processes the films, prepares them for reporting, and then transcribes the dictation, little is needed in the way of formal office procedure, but in clinics which employ dozens of workers and conduct hundreds of examinations each day there is confusion, delay, and costly waste of effort unless an orderly routine is set up and adhered to. There is a field here for recent graduates from university schools of business or for ex-soldiers with experience in

office management, and an opportunity, too, for the makers of office appliances.

Film Identification: In a large service it is not feasible to mark films by the simple procedure of introducing typewritten labels between film and screen as the cassettes are loaded. Instead, most laboratories use lead letters or numbers that the technician places on the table top or sometimes directly on the cassette. This method is better than nothing but has shortcomings so well known to radiologists that they need not be enumerated here. Photographing name, date, and number on the film after it has been taken to the darkroom and removed from the cassette requires that the darkroom technician be able to identify the top and the "butter side" of the film and has other practical disadvantages. I believe that there would be a market for a printer that employed x-rays rather than light and was located not in the darkroom but out in the exposing room near the film pass-box. To use such a printer, cassettes would have to be equipped with a small rectangular lead plate cemented to the bakelite front so that a corresponding segment of the film would be protected from radiation at the time the exposure was made, and for each patient there would have to be provided a small lead stencil bearing his name and number. The printer would contain a built-in stencil showing the name of the institution and a date stencil that could be changed daily. When all of the films of a particular patient had been made, the technician would insert the patient's name stencil into the printer and then, one by one, place the cassettes face up on the bed of the machine, with the segment of unexposed film registered directly above the stencil. A small, self-rectified unit located inside the printer would supply the beam of x-rays, the exposure being instituted by a foot-switch and terminated by a phototube. The radiation would pass upward through the back of the cassette and thus onto the film.

The resulting label would be uniformly legible, regardless of the density of the rest of the film, thus eliminating the necessity of punching dates and numbers onto the finished film and, though the initial cost of such a system would be considerable, it would be recovered shortly in a large service through savings in labor in the film room.

Stereoscopic Fluoroscopes: Stereofluoroscopes have come and gone with the seasons, but the final word on them remains to be said. Now that small, light-weight but rather powerful synchronous motors have become available, it should be a simple matter to construct a synchronous shutter that could be worn on a head band, and the provision of two tubes for the fluoroscope presents no difficulties. For non-stereoscopic fluoroscopy, the filament of one of the tubes would be turned off, but when stereoscopic vision was desired, both filaments would be lighted and x-rays would be produced alternately by the two tubes in phase with the alternations of the primary current. It would probably be necessary to provide a mechanical or electrical phasing device for the shutter.

Stereoscopic Filming: Two aspects of stereoscopic filming have long cried for attention—one needing merely the attention of good engineers, the other requiring the effort of an ingenious inventor. The engineering problem is the construction of a horizontal table for the rapid stereoscopic filming of such parts as the bowel, the kidney, and the gallbladder. The Potter grid would have to be of the reciprocating or the automatic reset type, and provision would have to be made for moving the first film out of the field and the second one in and for shifting the tube between exposures, but all of these are straightforward engineering problems.

The problem for the inventor is the old one of trying to obtain a pair of stereoscopic images of an infant's chest on a single film, the two exposures being made practically simultaneously. There is reason to believe that this is not incapable of accomplishment even with full-sized film, and when x-ray movies reach the stage of clinical feasibility, it probably will

be possible to make alternate exposures with an off-set x-ray tube so that each succeeding pair of images will be stereoscopic mates.

Cooling and Ventilating Darkrooms and Fluoroscopic Rooms: At the present time each radiologist must adapt to his own particular needs apparatus not specifically designed to meet them. Some profitable business awaits those manufacturers who are able to look beyond the sellers' market of the first few post-war years and are willing to expend thought and money for the design of cooling and ventilating units specifically suited to departments of roentgenology.

Microfilming: Now that apparatus for the microfilming of the chest has attained a reasonable degree of perfection, investigators and manufacturers must turn to the tougher problem of the microfilming of the heavier parts of the body. This will require lenses with greater speed and definition, obtained perhaps by radical alteration in design, fluorescent screens that are faster and of finer grain than those now in use, films that are faster and of better resolving power, and possibly special developer. If amplification of the fluoroscopic image yields to the effort that is sure to be expended upon it by investigators of the coming decade, that accomplishment may usher in universal microfilming over night. But improved microfilming need not wait upon that important innovation —it can be accomplished simply by the humbler process of improving the factors enumerated above.

Standardization: In closing, I wish to compliment x-ray manufacturers on the steps that have already been taken toward the standardization of certain parts of our equipment and to urge that they go as far as possible in this direction. They stand to gain almost as much as we by the introduction of high-tension cables with identical jacks at either end which can be used for either the anode or the cathode side and may be plugged into the transformer receptacles or the tube receptacles of every American manufacturer.

The number of different types of valve tubes should be reduced to an absolute minimum, and the over-all dimensions and the cathode and anode connections of valve tubes should be uniform, so that the tubes of any manufacturer may be used in the transformers of any other manufacturer. Obviously, the transition from chaos to order will be temporarily expensive and troublesome to manufacturer and user alike, and presumably during the transition period adaptors will have to be provided to allow the use of the new standard cables with tubes and transformers that antedate the era of standardization. Such difficulties will not be too great a price to pay, however, for the advantages that will accrue.

Division of Roentgenology
University of Chicago
Chicago 37, Ill.

Roentgen-Ray Tubes

W. D. COOLIDGE AND E. E. CHARLTON

Schenectady, N. Y.

SINCE ITS birth, the roentgen-ray tube has undergone many radical changes. The general method of producing roentgen rays is, however, still the same, namely by accelerating electrons to a high velocity and then suddenly stopping them by collision with a solid body, the so-called target.

Depending upon the method used in generating the electrons, roentgen tubes may be classified into two general groups,

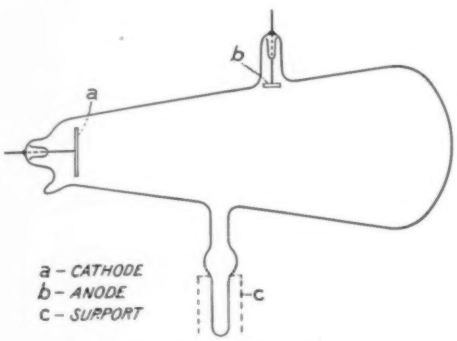


Fig. 1. Earliest type of roentgen tube.

gas tubes and high-vacuum tubes. In the first group, the electrons are freed from a cold cathode by positive ion bombardment, thus necessitating a certain gas pressure. In the second group, the vacuum is made as good as possible and the electrons are freed from the cathode either by heat, by bombardment from other electrons, or by the use of a potential gradient high enough to remove them electrostatically.

THE GAS TUBE

A. As First Used by Röntgen: The first roentgen tube (Fig. 1) was of a form previously employed by Crookes in his experiments on electrical discharges through rarefied gas. The electrons liberated by positive ion bombardment from the flat aluminum cathode were emitted in a direction perpendicular to its surface and, under the impressed voltage gradient, traveled in straight lines to the glass wall of the tube, where they generated roentgen rays.

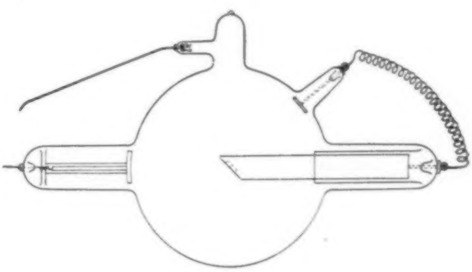


Fig. 2. Gas tube.

B. Early Modifications: This first roentgen-ray source was soon greatly improved by Campbell-Swinton through the introduction of a platinum foil target and by Professor H. Jackson through the substitution of a concave cathode for the original flat one. A later step of great importance was the addition of a device for regulating the vacuum. The early tubes were small and easily ruined, as so little energy was necessary to melt the thin electrodes and to overheat portions of the glass envelope.

C. Later Improvements: The power of the tubes was greatly increased by making them larger and with more massive cathodes and targets (Fig. 2). The development of the target in particular received much attention, resulting in a change from the use of a simple piece of sheet platinum to a platinum-faced disk of nickel brazed to a massive block of copper. This greatly increased the rate of heat flow away from the focal spot and, at the same time, increased the heat storage capacity.

A further substantial increase in tube power was later obtained by the develop-

ment of a tungsten-faced copper target, consisting of a disk of wrought tungsten onto which a large mass of oxygen-free copper had been cast in a vacuum. The principal properties desired in the target facing are high atomic number for maximum roentgen-ray efficiency, a high melting point, high thermal conductivity to allow maximum energies for a given size of focal spot, and a low vapor pressure to reduce the amount of target metal vaporized. Of all the chemical elements, tungsten combines these properties to the highest degree.

D. Limitations: The electrical characteristics of the gas tube were mainly determined by the gas pressure existing when the tube was carrying current. Owing to two opposing effects, this pressure could be either higher or lower than it was before the tube was energized. Heat development due to positive ion and electron bombardment tended to liberate adsorbed gas from the glass and from the electrodes and so to raise the gas pressure. On the other hand, there was an electrical pumping action during operation, tending to reduce the pressure.

Even though the pressure might remain constant, the electrical discharge through the gas tube was of a run-away character. To combat this and stabilize the discharge, it was necessary that the high-voltage source should have very poor regulation, that is, that its voltage should decrease rapidly as the current drawn by the tube increased.

If the pressure in the tube were too high, the voltage at all settings of the control would be too low. In the ordinary gas tube the only recourse then was to electrical clean-up. By operating the tube with current low enough to avoid appreciable heating, the gas pressure would gradually decrease.

If the pressure were too low, it could be increased by admitting gas from the regulator.[1]

[1] This assumed various forms, often consisting of a side-tube containing a chemical which upon being heated, as by the passage of a spark, would give off gas.

The initial pressure required for satisfactory operation was strongly dependent on the past history of the tube. The useful life was limited by the permanent electrical clean-up of gas and especially by the removal of adsorbed gas from the cathode. This last effect manifested itself by marked instability, finally becoming so bad that it was useless to add gas from the regulator as, on the application of high voltage, it would be immediately cleaned up. The tube could then be returned to its original condition only by rebuilding it with a fresh aluminum cathode, and it was necessary that this aluminum should contain hydrogen. It was apparently the gradual loss of hydrogen from the cathode that was most responsible for instability. This was, at least in effect, recognized by the manufacturers of such tubes, who carefully refrained from operating them any longer than necessary while connected to the pump.

As a result of the tube and circuit characteristics, it was difficult to know in advance what the voltage across the tube terminals during an exposure would be, and even difficult to know afterward what the roentgen-ray-producing voltage had been. The tube voltage was measured by means of a spark gap connected in parallel with the tube, but, as customarily used, this indicated the starting or break-down voltage, which was often much higher than the running voltage.

The size of focal spot was not constant but depended on the gas pressure and could vary appreciably even during an exposure. Not only this, but, as the pressure changed, the location of the focal spot could change also.

E. The Hot-Cathode Gas Tube: In the early hot-cathode tube of J. E. Lilienfeld (1), the main electrodes were the same as in the ordinary gas tube. By means of current flow between a pair of auxiliary electrodes, the cathode of which was heated, the gas of the tube was ionized, and, by varying the discharge current passing between the auxiliary electrodes, the conductivity between the main electrodes

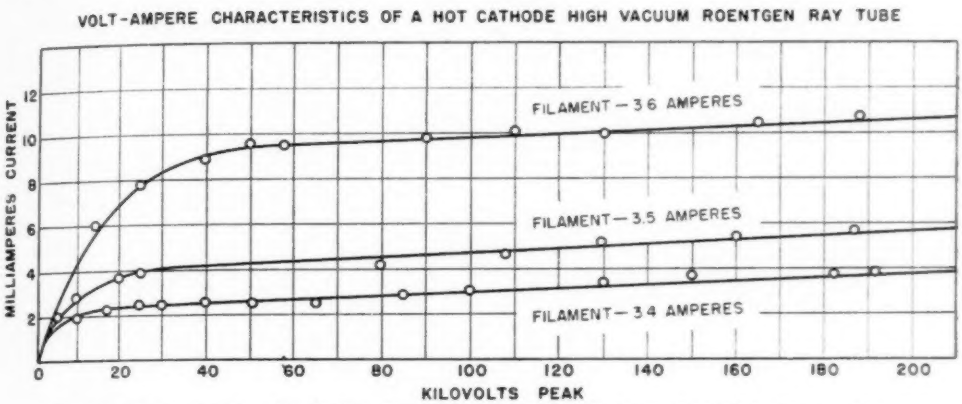


Fig. 3. Curves showing the relation of current to voltage in the hot-cathode high-vacuum tube.

could be controlled. The tube operated with a gas pressure somewhat lower than that of the ordinary gas tube. It was still a gas tube, however, and was not operable if the pressure became too low.

THE HIGH-VACUUM TUBE

Most of the troubles experienced with gas roentgen tubes could be associated with the gas itself and the positive ion bombardment that took place when that gas was present. It was very desirable to get rid of the gas, but this made it imperative to have some other mechanism for getting electrons out of the cathode.

Edison in his work on the incandescent lamp had shown that, in the vacuum of the lamp, current could be made to flow from the hot filament to an anode. Much additional light had been shed on this phenomenon by the work of O. W. Richardson (2) and others, connecting electron emission with the temperature of the hot body. The general belief had come to be, however, that the whole hot-cathode effect was due to gas contained in the cathode itself and that no current would flow from a hot cathode which had been completely freed from gas. Irving Langmuir's studies (3) of electron emission from hot tungsten lamp filaments demonstrated, however, that electron emission not only persisted in high vacuum but was favored by getting rid of the last traces of gas in the filament and other parts of the tube. In this way he was able to realize conditions which were stable and reproducible.

A. The Hot-Cathode High-Vacuum Tube: Coolidge (4), encouraged by the work of Langmuir, made a roentgen-ray tube with a hot tungsten filamentary cathode and a solid tungsten target and found that, even with the relatively high voltages and large masses of metal involved, it was possible to get and to maintain a vacuum sufficiently high to permit of stable and reproducible operation.[2] The relation of the current to the impressed voltage in a tube of this type is shown in Figure 3. The different curves are for different filament temperatures and show that, over the operating range of roentgen-ray voltages, the discharge current is practically independent of voltage.

In one of the first Coolidge tubes (Fig. 4) the cathode consisted of a spiral tungsten filament mounted behind a centrally perforated tungsten or molybdenum focusing disk, both filament and disk being set in the cathode side-arm, and the anode consisted of a circular tungsten disk attached to the end of a tungsten support rod. From the earliest form the design soon changed to that of Figure 5, with its

[2] The idea of using a hot cathode in a roentgen-ray tube was not new at this time, but the principle had never been successfully applied in a vacuum so good that positive ions did not play either an essential or harmful role. The hot cathode of A. Wehnelt and W. Trenkle (5) employed a lime-coated hot cathode as a main electrode but was not operable at useful roentgen-ray voltages.

different cathode construction and its more massive target.

B. The High-Vacuum Tube with Auxiliary Hot Cathode: J. E. Lilienfeld (6) later developed a type of hot-cathode tube in which the primary electrons were produced from a hot filament in a side-tube, the so-called ignition chamber. These primary electrons were caused to bombard the inside of the perforated main cathode, where they liberated secondary electrons. The electrons passing through the perforated cathode were accelerated, by the high electrostatic field, toward the target, with the production of roentgen rays. The tube was more complicated than the simple hot-cathode type and apparently possessed no advantages over the latter.

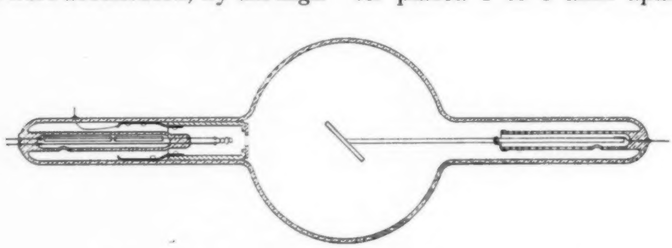


Fig. 4. Earliest type of hot-cathode high-vacuum tube.

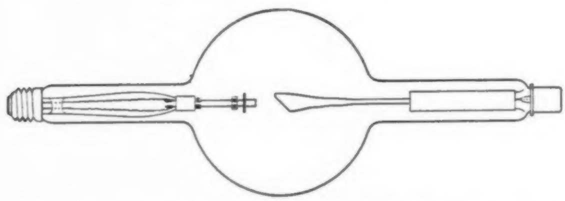


Fig. 5. First commercial model of hot-cathode high-vacuum tube.

C. The Field-Current Tube: In the gas tube the emission of electrons from the cathode was produced by positive ion bombardment, and in the hot-cathode tube by thermionic effect. Experimental phenomena involving the pulling out of electrons from cold metals by high potential gradients have been observed and studied by many investigators.[3]

H. A. Rowland, N. R. Carmichael, and L. J. Briggs (8) made early experimental tubes in which the cathode and anode consisted of aluminum wires mounted with their co-operating ends only a millimeter apart. With the best vacuum which they could produce, these workers found that current would pass through such a tube between the ends of the electrodes, generating roentgen rays at a minute point on the end of the electrode which functioned as anode.

R. W. Wood (9) found that he could pass discharges from an induction coil between platinum spheres 1.5 mm. in diameter placed 1 to 5 mm. apart in a highly evacuated chamber over mercury, and that very penetrating roentgen rays were produced at the anode sphere. The experiments of both Rowland and Wood were clearly examples of field-current discharge.

Lilienfeld (10) developed a roentgen tube of this type in which the cathode was a wire with a pointed tip, placed a few millimeters from the target and facing a depression in the latter which served as the focal area. The function of this depressed area was to localize the focal spot which otherwise wandered about.

C. M. Slack and L. F. Ehrke (11) have developed a field-current tube for very rapid roentgenology, as for example, to depict a bullet in flight in its passage through an obstacle.

[3] K. T. Compton and I. Langmuir (7) have reviewed the results of this work on field currents.

The electrical characteristics of the field-current tube resemble those of the gas tube in that the current and voltage are not independent of each other. Like the latter, it therefore does not have the flexibility of the hot-cathode tube, nor does it have the stability.

THE HOT-CATHODE HIGH-VACUUM TUBE

A. General Considerations

(*1*) *Inherent Advantages:* The main advantages of the hot-cathode high-vacuum tube over the gas tube are:

(*a*) *Flexibility:* Voltage and current may be independently varied at will.

(*b*) *Voltage:* The tube can be designed for much higher voltage.

(*c*) *Electrical Stability:* This permits more accurate reproducibility of results.

(*d*) *Non-Varying Size and Position of Focal Spot.*

(*e*) *Size of Tube:* For a given energy input the tube can be made much smaller, thus facilitating roentgen-ray protection and giving increased latitude in the design of auxiliary equipment.

(*f*) *Design of Tube:* Greater flexibility is permitted in the use of hollow anode construction to facilitate adequate roentgen-ray protection, to reduce scattered and stray radiation, and to generate roentgen rays at any desired location in the vacuum envelope.

(*g*) *Location:* As visual inspection during operation is not required, the tube can be entirely enclosed, out of sight, facilitating both electrical and roentgen-ray protection.

(*h*) *Operation:* This can be directly from a transformer without auxiliary rectifying device, thus making possible for many purposes a very simple outfit.

(*i*) *Long life.*

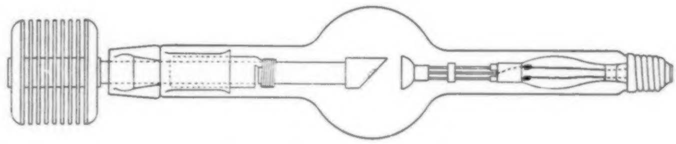


Fig. 6. Radiator-type tube.

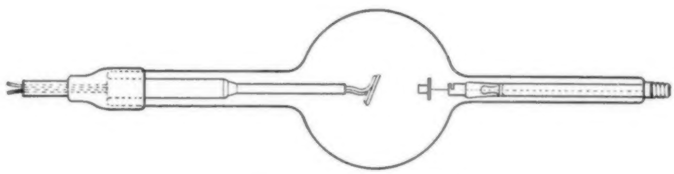


Fig. 7. Water-cooled therapy tube.

(*2*) *Various Forms:* Many forms of hot-cathode tube of the high-vacuum type have now been developed to cover a wide range of usefulness. They vary in size from that of an oil-immersed dental tube with a bulb diameter of 1 1/2 inches and a length of 4 inches, up to that of the 1,400,000-volt tube at the National Bureau of Standards (34), which is 12 inches in diameter and 24 feet long.

The "Universal" tube (Fig. 5) with a solid tungsten target is a form that has been used for both diagnostic and therapeutic purposes for many years. As its target may get very hot, it is intended to be operated only with rectified current.

Another typical design, for diagnostic work only, is a radiator-type tube (Fig. 6) built with a copper-backed tungsten target, that operates over a wide range of energy ratings and is capable of rectifying its own

current provided the energy used is not sufficient to heat the focal spot to a temperature at which appreciable electron emission would take place.

Still another type, with a high energy rating for continuous operation, is a water-cooled tube (Fig. 7) especially developed for therapeutic use.

A special form of therapy tube has been developed for internal body cavity work (12).

For use at very low voltages (say 1,000 to 10,000 volts) thin beryllium windows may be employed.

(3) Current Control: The electrons are emitted from a hot tungsten filament, and the tube can be so designed that the current flowing from cathode to anode is either emission limited or space charge limited. In the former case, over the operating range of voltage, all of the available electrons from the filament are used, and the milliamperage is, therefore, dependent only on filament temperature. In the latter case, the filament is always operated at a temperature in excess of that required to emit the desired number of electrons, and the milliamperage is limited by the negative space charge due to the electrons, the amount of this space charge being determined by the electron velocity and hence by the voltage used.

The tube used for the data contained in Figure 3, when operating with a filament current as high as 3.6 amperes, was evidently emission limited from about 50 kv. upward, while for lower voltages it was space charge limited.

For maximum flexibility, it is desirable to design the tube to be emission limited in order that any desired current can be used with any desired voltage. With a space charge limited tube, the lower the anode voltage, the less current can be made to flow through the tube.

With an emission limited tube the current changes very rapidly with filament temperature, as shown in Figure 3. This makes it desirable to have a constant source of voltage to heat the filament. Storage batteries were used at first, but have since been generally replaced by transformers for filament excitation. The effect of fluctuations in line voltage is minimized by some form of stabilizer, such as the Kearsley (13) or constant-current transformer type (14).

(4) Control of Quality and Intensity of Radiation: The hot-cathode tube, unlike its predecessor, permits of the independent control of the quality and intensity of roentgen-ray output. The quality is determined primarily by the applied voltage and secondarily by wave form and target material. It is also somewhat dependent on the angle, referred to the tube axis, at which the roentgen rays are emitted. These conditions all being fixed, the intensity is simply proportional to the current.

The roentgen rays produced are in general of two kinds, those characteristic of the target material and those which are independent of target material and, like white light, include a considerable range of wave lengths. Of the latter, the *shortest* wave length, λ_0, bears the following simple relation to the voltage:

$$\lambda_0 = \frac{12340}{\text{voltage}}$$

in which λ_0 is expressed in Ångström units (1 Ångström = 10^{-8} cm.). For practical purposes, the *effective* wave length can in general be considered to be about twice the minimum value.

In comparison with visible radiation, which lies between 4,000 and 7,000 Ångströms, roentgen rays in use today range in effective wave length from about 0.00025, corresponding to 100,000,000 volts, to 25.0 Ångströms, corresponding to about 1,000 volts. Table I gives the voltage range and the corresponding effective wave lengths of radiation employed for various medical purposes.

(5) Radiation from Other than Focal Area: In the hot-cathode high-vacuum tube, even with perfect focusing of the primary electrons, there is in general a considerable roentgen-ray production from the surface of the target outside of the focal area (15). This is due to high-velocity

TABLE 1: VOLTAGE RANGE AND EFFECTIVE WAVE LENGTH FOR MEDICAL PURPOSES

Application	Voltage	Effective Wave Length
Dental roentgenography	50,000 to 70,000	0.5 to 0.4 Å.
General roentgenography	30,000 to 100,000	0.8 to 0.24 Å.
Therapy	1,000 to 1,000,000	24.7 to 0.025 Å.

secondary electrons emitted from the focal spot. They cannot go, as in the gas tube, straight to the glass walls, as these are, in the high-vacuum tube, at relatively close to cathode potential. They must therefore return to the anode, where their impact gives rise to the roentgen radiation which may be observed, by means of a pinhole camera, as coming from other than the focal area. For diagnostic purposes this parasitic radiation would be troublesome if it were much more intense than it is. Its effect could, however, be reduced, if necessary, by special design.

(6) *Angular Distribution:* The intensity of the rays is dependent upon their direction with respect to that of the cathode rays which produced them, and the relation of these two quantities is strongly affected by the voltage used. At voltages much below a million it is customary, for most purposes, to use roentgen rays emanating from the face of the target, which it is convenient to designate as the "reflected rays," while with higher voltages the rays passing through the target ("transmitted rays") are more often employed. In the case of tubes intended for use in body cavities and employing relatively low voltages, transmitted rays are ordinarily used.

Penetrating power is also affected by direction of emission but not to so great an extent as intensity.

Measurement of the intensity of the reflected rays from a "Universal" tube (Fig. 5) showed (16) a maximum in close to the direction of the generally used "central ray," decreasing to half this value at an angle (measured around the girdle of the tube) of about 75 degrees on either side. This was with a voltage of 127,000. Petrauskas, Van Atta, and Myers (17), using the unfiltered "transmitted" beam from a target placed at right angles to the cathode rays, found at 2,350,000 volts maximum roentgen-ray intensity close to the central ray, dropping to half value at about 37 degrees from this direction. Dr. Kerst (18), working with the induction electron accelerator at 20,000,000 volts, found the intensity dropping from maximum to half value in about 4 degrees. With the 100,000,000-volt induction electron accelerator operating at full voltage, the corresponding angle is only 1 degree (19).

(7) *Efficiency of Roentgen-ray Production:* The efficiency is directly proportional to the atomic number of the target metal and increases rapidly with voltage. Rutherford and Barnes (20), operating a hot-cathode tungsten-target tube from a static machine, obtained at 96,000 volts an efficiency of transformation of cathode-ray energy into roentgen-ray energy of 0.2 per cent.

Recent measurements made by Petrauskas, Van Atta, and Myers (17) with the help of the large Van de Graaff static machine at the Massachusetts Institute of Technology show the following dependence of efficiency upon voltage, the rays being taken from a gold target and in the forward direction (that of the cathode rays) and corrected for absorption in the target.

Voltage in Millions	Efficiency (Measured)	Efficiency (From Theory)
2.35	10.4%	8.3%
1.63	5.8%	5.6%
0.90	3.0%	3.4%

(8) *Operation Self-Rectified:* Under normal conditions, current can pass through the tube in but one direction. If, however, any portion of the focal spot is allowed to become heated to the temperature of the cathode filament, on alternating current excitation, current will flow through the tube in both directions. The resulting electron bombardment of the cathode will raise its temperature, thus increasing the target bombardment and so

causing run-away. While, then, the tube may be satisfactorily operated from alternating current, serving as its own rectifier, with any given design the capacity of the tube is always greater when operating from a unidirectional source.

(*9*) *Limit to Allowable Energy Input:* Even with rectified current, the energy input must not be so high as to cause appreciable vaporization of the tungsten from the focal spot, for the tungsten vapor, by becoming ionized, may cause instability, signalized by rapid rise of current.

vent the melting of the copper at its hottest point just behind the focal spot.

In this same connection, cathode design is also important, as it determines not only the size but also the distribution of energy over the focal spot. This last must be as uniform as possible, as, for a given area, the limit to allowable energy input will be set by the hottest part of the focal spot.

(*2*) *Power Supply:* For the maximum possible roentgen-ray intensity per unit of focal area, direct current at constant potential would be employed to operate the

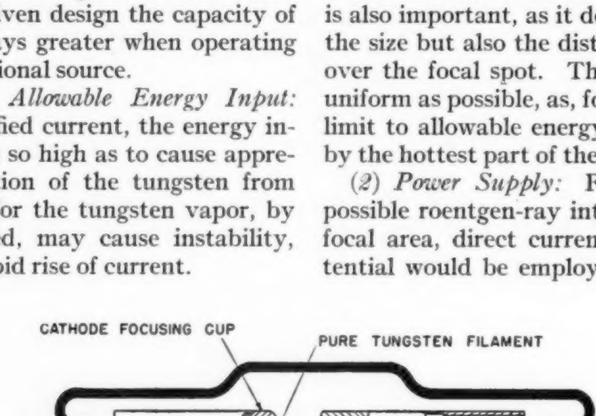


Fig. 8. Hot-cathode line-focus tube.

B. *Tubes for Roentgenography*

(*1*) *Considerations Affecting Target Design:* For the production of roentgenograms of the highest technical quality, the tube should be so designed and constructed as to permit the production of the greatest possible roentgen-ray intensity, consistent with satisfactory tube life, from a given size of focal spot. The target in most general use is the composite one developed earlier for the gas tube and having a tungsten facing of a certain thickness in good thermal contact with a large mass of copper. The copper with its high heat conductivity serves to take the heat away rapidly from the focal spot, distributing it to its large mass which serves as a reservoir, from which it can later escape by radiation and conduction before the next operation of the tube. The thickness of the tungsten facing will be chosen just sufficient to pre-

tube. As single-phase alternating-current high-voltage apparatus is much simpler, however, it is ordinarily used. With alternating-current high-voltage supply, the maximum available intensity per unit area is appreciably greater if an auxiliary rectifying device, such as a full-wave kenotron rectifier, is employed; here again, however, a simpler system, in which the roentgen tube rectifies its own current, is often used.

(*3*) *Line Focus:* In the line-focus tube (21, 22), as shown in Figure 8, a rectangular electron beam is used to provide a projected square focal spot in the useful roentgenographic direction. The gain obtainable by this method (23) is determined by the minimum angle of the target face with the direction of the useful beam that will provide adequate film coverage for the largest film at the minimum distance to be used. In general, a 20-degree angle has been found to be the most practical for

roentgenographic uses. For this, the gain over a 45-degree angle may be as much as threefold. In some special tubes 15 degrees is used and even 10-degree target angles have been employed. The gain for 15 degrees may be about fourfold, and for 10 degrees as much as fivefold. The coverage at 10 degrees is, however, so small that a minimum of 6 feet target-to-film distance should be used. There is, furthermore, this disadvantage in the use of so small an angle as 10 degrees, that the development, with use, of any considerable roughness of the focal area may cause serious loss of roentgen-ray intensity in the useful direction.

(*4*) *Variety of Focal Spot Sizes Desirable:* Various subjects for roentgenography may require widely different amounts of radiation, as well as different limits in time of exposure. To facilitate the revelation of as much detail as possible in all cases, tubes are made with a variety of focal spot sizes ranging from about 1 to 9 mm. For focal spots of these sizes the allowable loading of a tungsten target 3 mm. thick, cast in copper, varies from about 50 to 600 watts per square millimeter, depending on size of focal spot and time of exposure. Figure 9 gives safe values for tubes operating on single-phase, full-wave rectified 60-cycle current. The smaller focal spots will stand higher specific loadings because the surrounding tungsten is more effective in heat removal from them than in the case of larger focal areas.

(*5*) *Double Focus:* To simplify the technic of roentgenography of the various parts of the human body, double-focus tubes are often employed. In these tubes, by means of a double cathode, either of two radically different sizes of focal spot may be used, the smaller to give fine detail in body extremities and the larger for thicker parts requiring more energy.

(*6*) *Rotating Target:* The loadings of a stationary target cannot safely exceed certain definite values. By rapid rotation of the target, however, relatively cold metal can be constantly advanced to take the electron bombardment, and so the permissible loadings can be greatly increased. Such rotation was suggested by R. W. Wood in 1897, and later by Rollins and Elihu Thomson. In 1915 Coolidge reported on experimental work with a tube in which the rotating target was supported by ball bearings and ran at 750 r.p.m., yielding a gain of two- or threefold in the amount of energy which could be carried on a given focal area.

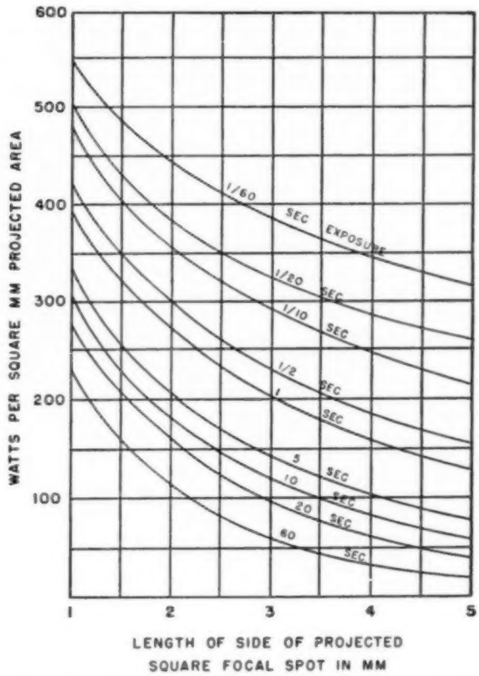


Fig. 9. Tungsten-target focal spot loading data: single phase, full wave, 60 cycles; line focus 20° target angle.

The target is best rotated by means of an induction motor whose stator is without and whose rotor is within the tube and carries the target. A commercial tube embodying this principle and with a plain sleeve bearing was described by Bouwers (24) in 1929.

Ball bearings, to be used successfully, must be made of metal which is hard at the temperatures to which they are subjected in this application. This requirement is fulfilled by certain precipitation hardening alloy steels.

In our early ball-bearing rotating-target tubes the drastic heat treatment required for the exhaust removed the last trace of lubricant from the bearings. As a result, the friction was high and, to operate at all well, it was necessary that the bearings have appreciably more than the customary radial clearance, which made them very noisy. It has since been found that this difficulty can be overcome by coating the bearings either with a thin film of barium (26) or silver (25).

In the rotating-target tube shown in Figure 10 rotation is combined with the use of the line focus. The gain to be derived by rotation is shown in Figure 11 for various speeds (27).

In rotating-target tubes on the market today a speed of 3,000 to 3,500 r.p.m. is employed. The gain in loading as compared to a stationary-target tube varies with the exposure time and is about as the square root of the speed.

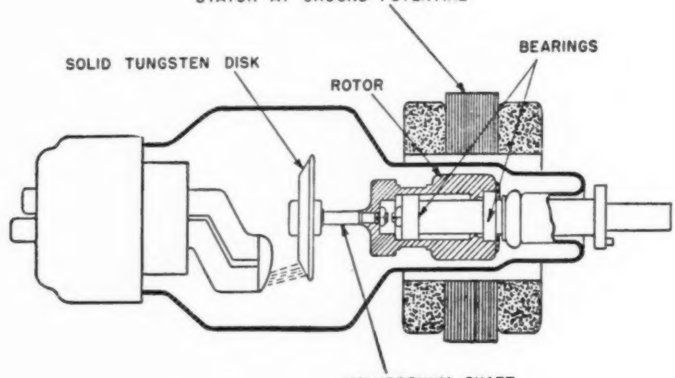


Fig. 10. Rotating target tube with stator in position.

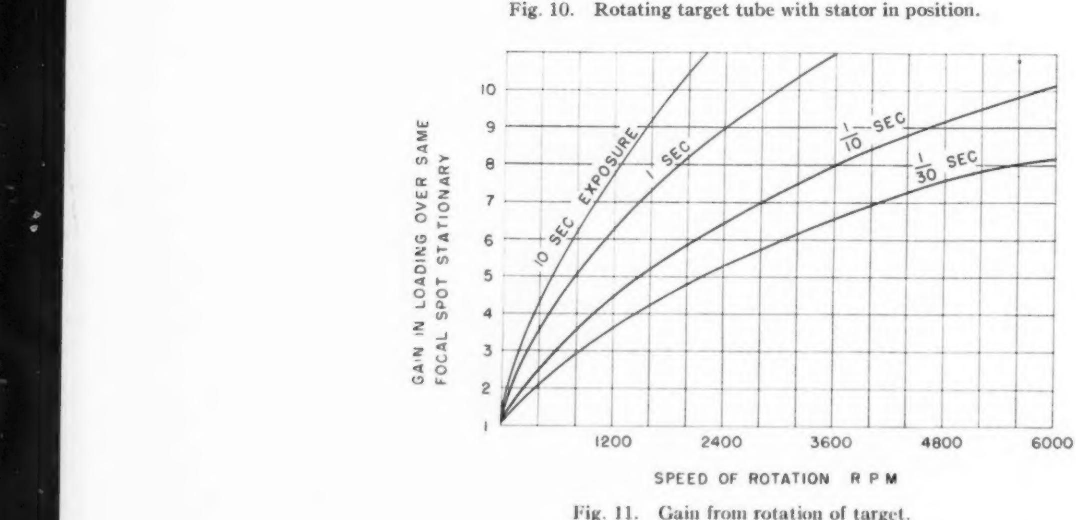


Fig. 11. Gain from rotation of target.

C. *Tubes for Fluoroscopy*

In the medical field the same tubes used for roentgenography are in general suitable for fluoroscopy, as the requirements

of the latter service have been considered and met in the design of roentgenographic tubes. Most medical fluoroscopy is done with a current of 2 to 5 ma. at voltages from 40 to 85 kv.p., depending upon the technic employed and the part of the body being studied. In this service the tube may be energized for a few seconds or for several minutes at a time.

For industrial fluoroscopic work, special tubes may be required, as currents of as high as 15 to 30 ma. at voltages of 85 to 250 kv.p. may be needed.

As the detail recognizable in fluoroscopy is not as great as in roentgenography, exact size of focal spot is not as important as in the latter service. For the requisite long time of operation, the total heat developed is considerable, and the anode must be capable of handling it.

In "spot-film" medical roentgenography the area to be delineated is chosen by fluoroscopy. In those cases, as of the stomach, where motion is involved, the time for making the exposure is chosen by the same means. Fluoroscopy is then rapidly followed by roentgenography, thus imposing heavy duty on the tube. This may necessitate, for cooling the target, the use of a blower or liquid circulating system.

D. *Tubes for Therapy*

(*1*) *General Considerations:* In therapy the main requisite is to provide a sufficiently large beam of the desired kind of radiation having essentially uniform intensity over its entire cross section. The skin-focus distance, dictated in general by depth-dosage considerations, ranges from about 25 to 100 cm., and the largest field to be covered is about 20 × 20 cm. The size of focal spot is relatively unimportant. Usually round, it varies from about 1/4 to 1 inch in diameter.

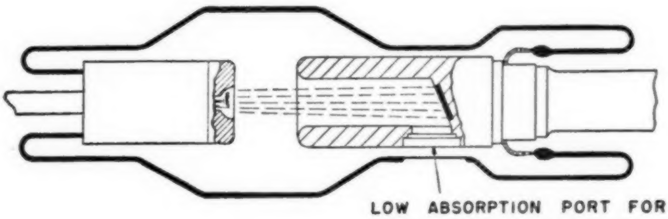


Fig. 12. Self-rectifying therapy tube with hooded anode construction.

Treatment periods range from several minutes up to as much as an hour in special cases, so that the duty of the tube for all practical purposes must be considered as continuous. This means that the main design problem in tubes for therapy concerns the removal of heat from the anode. This may be accomplished by using a solid tungsten target, as in Figure 5, and allowing this to heat up to a high temperature where it can radiate the requisite amount of energy, or a composite tungsten-copper target may be cooled by rapidly flowing water or oil. In the case of oil-immersed tubes a heavy anode stem may be employed to conduct heat out to the oil, where it may be dissipated by natural convection.

(*2*) *Superficial Therapy:* The voltage employed in superficial therapy may be as low as 5,000 or 10,000, in which case the radiation would not be transmitted to a useful extent through the ordinary glass envelope. For such work a thin window of beryllium metal may be employed.

(*3*) *Intermediate Therapy:* Therapy tubes for voltages in the neighborhood of 140,000 differ little, if any, from tubes intended for roentgenography.

(*4*) *Deep Therapy at Voltages from 200 to 400 kv.p.:* Voltages from 200 to 400 kv.p. make possible the treatment of the most deeply seated tumors in the body. Tubes produced today for these voltages have a thick-walled pyrex envelope to

avoid puncture. They usually are cooled by circulating oil in the back of the target and at 200 kv. may well carry as much as 10 or even 30 ma. They may be operated from either a rectified or unrectified current source. The performance of such tubes when operating directly on alternating current is considerably improved by the use of a hooded target, as shown in Figure 12. The presence of the hood reduces the number of secondary electrons emanating from the target and reaching the glass envelope, where otherwise their presence in sufficient number might lead to puncture.

For 400,000 volts, tube design is much the same as for 200,000 volts except that all physical dimensions have to be increased. At this voltage, less current is in general required, and at present 5 ma. is in common use.

(5) Deep Therapy at Still Higher Voltages: During the last few years much interest has been shown in the therapeutic use of voltages of a million or more. For such voltages, and even for much lower ones, the tube can to advantage be sectionalized (28) and provided with a multiplicity of hollow accelerating electrodes. This gives a more uniform gradient along the length of the tube and reduces dielectric stresses in the glass envelope. At the same time it serves to prevent the formation of troublesome field currents which may otherwise take place from the cathode, due to the stronger field which exists there in case only a single pair of electrodes is used. The accelerating electrodes are usually connected to suitable taps in the high-voltage source. With such high voltages the target may be so designed as to make possible the use of either the radiation coming through the target or that given off from the face. At these voltages the intensity is greater in the "transmitted" than in the "reflected" beam and the effective wave length is shorter.

Such tubes may either be operated while

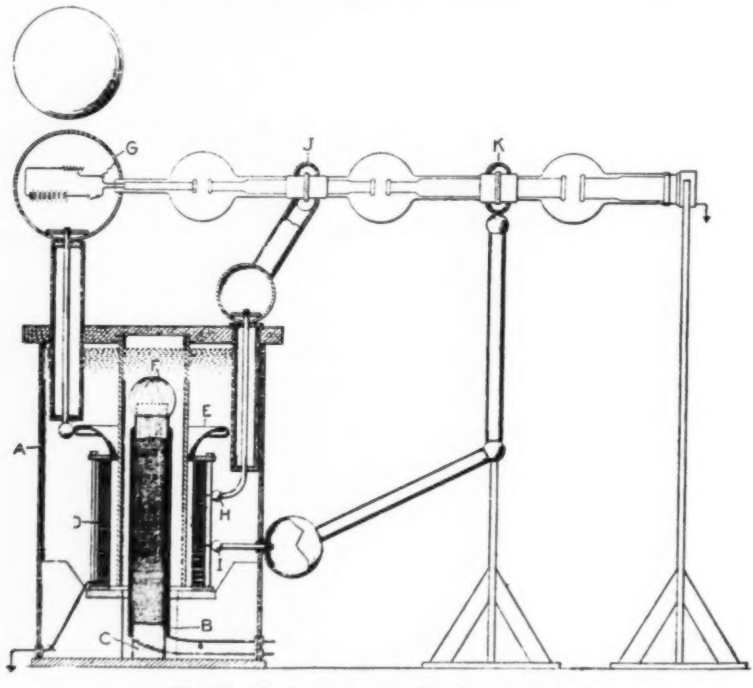


Fig. 13. Early experimental multisection tube.

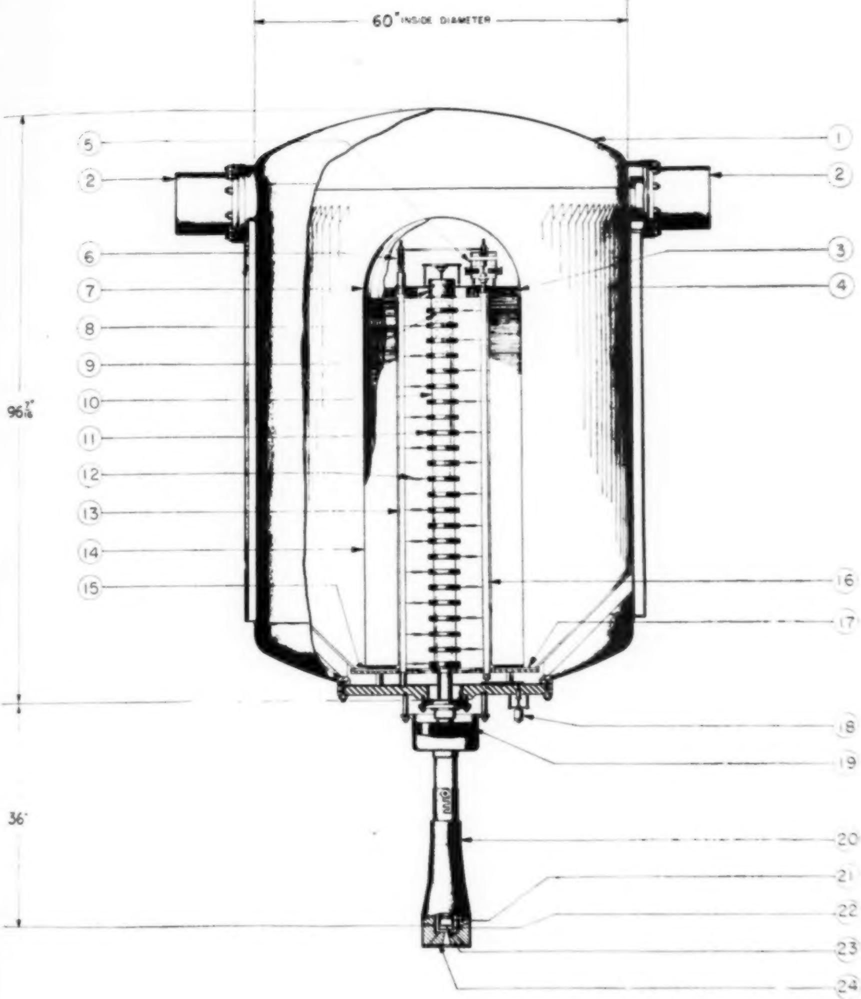


Fig. 14. Mobile two-million-volt roentgen-ray outfit.

1. Steel tank
2. Cooler
3. End turn filament coil
4. Laminated shield
5. Variable reactor
6. Spring for tie rod
7. Slotted brass shield
8. Cathode assembly
9. First intermediate electrode
10. Glass envelope
11. Shields around roentgen ray tube
12. Tap lead
13. Glass tie rod
14. Secondary coils
15. Primary winding
16. Insulating filament-control shaft
17. Laminated steel bottom
18. Filament control motor
19. Focusing coil
20. Lead shield
21. Water jacket
22. Extension chamber
23. Tungsten target
24. Lead diaphragm

undergoing continuous evacuation from a suitable pumping system or they may be sealed off. A diagram of an early experimental induction-coil installation is shown in Figure 13. This was followed by commercial transformer installations in which the tube consisted of a multiplicity of cylindrical glass sections cemented or sealed together and provided with hollow cylindrical accelerating electrodes.

With the advent of the low-frequency resonance transformer (29), it became possible to put the tube inside of the transformer. This facilitates the connection of the various accelerating electrodes to the transformer and at the same time provides electorstatic shielding for both the tube and the connecting leads.

An early one-million-volt example of this type of equipment was installed in 1939 at the Memorial Hospital in New York (29). It was stationary and arranged for therapeutic use with either the reflected or transmitted beam. It had a 12-section tube which was continuously pumped. A later similar one-million-volt outfit (30), developed originally for industrial roentgenography, is smaller, has a sealed-off tube, and can be operated in any position.

A similar outfit (31), also with sealed-off tube and operable in any position, has been developed for 2,000,000 volts. The cut-away drawing of Figure 14 shows the tube in position inside the high-voltage resonance transformer.

It seems entirely feasible by this method to go still higher, to perhaps as much as four or five million volts.

E. Diffraction Tubes

For roentgen-ray diffraction work it is desirable to have radiation which is as nearly as possible monochromatic. This is obtained by using not the general roentgen radiation, but that characteristic of the target material. As, for different purposes, different wave lengths are required, this necessitates the use of tubes with different target metals, as, for example, copper and molybdenum. The voltages used for these two metals are usually 30 to 35 kv. for copper and 35 to 45 kv. for molybdenum, and the characteristic wave lengths are 1.539 Å. for copper and 0.709 Å. for molybdenum. These radiations are usually taken out through thin beryllium windows (33). To increase the capabilities of the diffraction tube, it may be provided with a number of windows, thus making possible the simultaneous study of a corresponding number of specimens. Such a tube is shown in Figure 15.

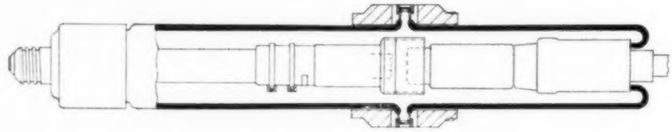


Fig. 15. Diffraction tube.

THE PROTECTION PROBLEM

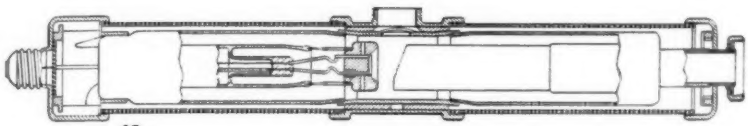
Protection must be provided from both the roentgen rays and the high voltage. This is accomplished much more readily with the modern type of tube than with its predecessor, and for two reasons: first, the modern tube can, for the same service, be much smaller than the gas tube; second, it does not need to be seen during operation.

A. Roentgen-Ray Protection: As roentgen rays are emitted in all directions from the front of the focal spot, lead or its equivalent is used either in the walls of the tube or in the tube enclosure to absorb all but the useful beam. The electrodes of the tube are usually sufficiently massive to guard against most of the radiation which would otherwise escape from the ends.

Roentgen-ray protection is readily secured in the Metalix tube (32) of the Philips Company, with its grounded metal envelope surrounding the central portion

(Fig. 16). An alternative construction is shown in Figure 17. The same result is also secured by the construction shown in Figure 18, in which the radiator-type tube of Figure 6 is provided with a two-piece, thick-walled shield of glass having a high lead content.

tube envelope and more particularly in 1,000,000- and 2,000,000-volt tubes in which the roentgen rays are transmitted through the target as well, roentgen-ray protection is to a great measure facilitated by surrounding this chamber with an adequate wall of lead.



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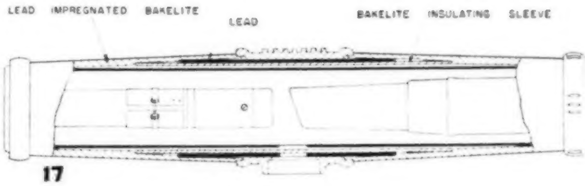

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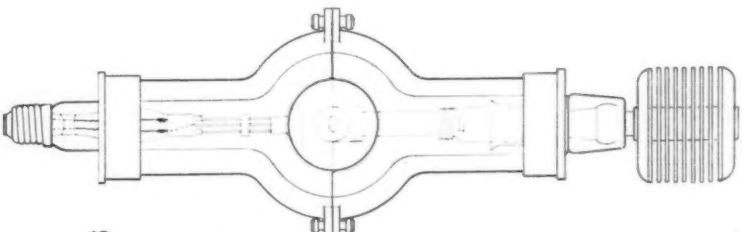

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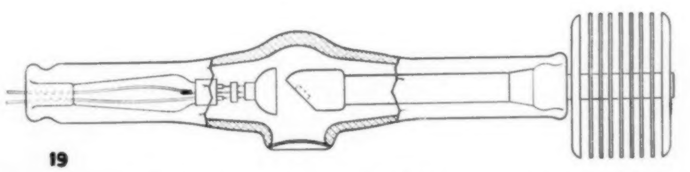

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Figs. 16–19. Protected tubes. Fig. 16. Metalix tube. Fig. 17. Alternative construction of roentgen-ray protected tube. Fig. 18. Radiator tube in lead glass shield. Fig. 19. Roentgen-ray tube with vacuum envelope of protective lead glass.

The small tube of Figure 19, developed for medical diagnostic use with a portable outfit, derives its roentgen-ray protection from its very thick envelope of glass having a high lead content. The useful beam of rays is taken out through a lead-free glass window.

In tubes in which the target is located in a metal extension chamber attached to the

B. Electrical Protection: Full electrical protection is obtained by enclosing the entire high-voltage circuit in grounded metal. Two different methods are used:

One of these is illustrated by Figure 20, which shows a small roentgen tube together with filament transformer and high-tension transformer all in the same oil-filled metal case. Such a system is exten-

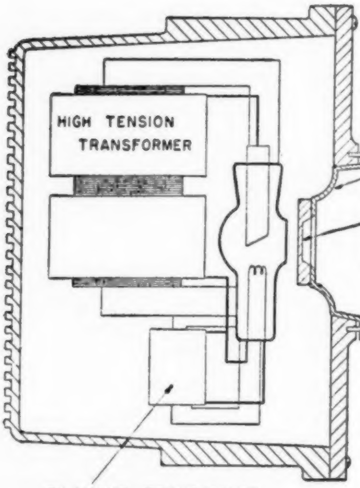

Fig. 20. Roentgen-ray tube and transformer in same oil-filled metal container.

sively used for dental work, therapy, and other applications. In some cases, as in the outfit shown in Figure 14, compressed gas is used in place of oil for the high-voltage insulation.

The other method of securing electrical protection consists in housing the tube in a grounded oil-filled metal enclosure, as shown in Figure 21, and connecting it to the high-voltage source by means of heavily insulated flexible metal-clad cable. For rapid medical roentgenography, this method is preferable to the former, as it permits the use of a powerful high-voltage source of rectified current while retaining relatively light weight in the part which has to be moved, namely, the tube and its enclosure.

With both systems, lead or its equivalent will be used around the tube, and the metal enclosure can be made not only to provide electrical protection but also to increase the roentgen-ray protection.

INDUCTION ELECTRON ACCELERATOR

For the production of roentgen rays corresponding to voltages in excess of a few million, the induction electron accelerator is today the most attractive looking device. It has proved successful in the 20,000,000- and the 100,000,000-volt sizes (18, 19) and can presumably be used for still higher voltages. The tube is a hot-cathode high-vacuum device consisting of a hollow toroid of glass or other insulating material about 18 inches in diameter for the 20,000,000-, and 6 feet in diameter for the 100,00,000-volt sizes. The elec-

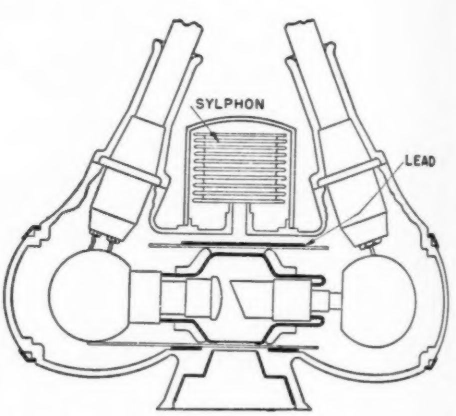

Fig. 21. Roentgen-ray and electrically protected tube enclosure.

trons from a hot filament are electrostatically focused and are accelerated with some 20,000 volts or more in a direction tangential to the axis of the toroid. By means of a time-varying magnetic field they are further accelerated and focused and constrained to follow a circular path within the tube. In the case of the 100,000,000-volt machine they encircle the field 250,000 times in 1/240 second, receiving on an average a 400-volt push each time around. After traveling in this way in a circular path for about 800 miles and receiving the energy which they would have had if they had passed between two electrodes having a potential difference of 100,000,000 volts, they are caused to leave their circular orbit and impinge upon a tungsten target, where they produce roentgen rays. Or they may be caused to leave the circular orbit at any desired earlier time in the magnetic cycle, thus producing roentgen rays corresponding to any voltage up to 100,000,000.

The electron current in the beam is very low compared with that which has ordinarily been used in roentgen tubes, and of the order of a microampere, depending to a great extent on the frequency employed for the time-varying magnetic field.

The tubes may be built either as unitary structures or in sections cemented together and continuously pumped. The 100,000,000-volt tube is shown in Figure 22. It consists of 16 pie-shaped sections of heat-treated Pyrex glass having an elliptical cross section 8 × 4 7/8 inches. The ends of the sections are ground flat and smooth and to the correct angle, and the joints, coated on the outside with glyptal paint, are vacuum tight.

The induction electron accelerator, as a multimillion volt roentgen-ray source, will be extensively used in scientific research and should also find therapeutic and industrial applications.

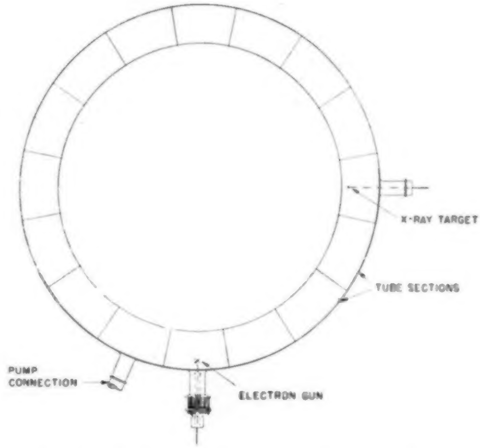

Fig. 22. Induction electron accelerator tube for 100,000,000 volts.

SUMMARY

During the fifty years since Röntgen's great discovery, the roentgen tube, from a very uncertain and relatively feeble source of radiation, has been developed into a powerful precision tool of great stability, flexibility, and ease of control, permitting of the accurate reproducibility of results and capable of operation over a wide range of current and voltage. In the diagnostic field, definition for a given speed has been, through the years, greatly improved. For therapeutic work, the high-voltage rays now obtainable make possible the treatment of deep-seated lesions. The various industrial applications make use of the entire range of wave lengths which can be derived from the tube, at least corresponding to voltages up to a few million. The gradual increase which has taken place in the allowable voltage has been attended by a corresponding extension in the range of usefulness of the rays in industry. Much roentgen-ray protection can now be built into the tube itself, and the modern tube lends itself readily to the attainment of complete electrical protection. From the point where only an expert, with years of experience, could get the most out of it, the tube has come to be as easy to operate as an incandescent lamp.

Research Laboratory
General Electric Co.
Schenectady 5, N. Y.

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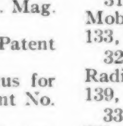
1895  1945

The Development of Roentgen Diagnosis

LEO G. RIGLER, M.D.

University of Minnesota, Minneapolis, Minn.

The discovery of a new type of radiation by Wilhelm Conrad Röntgen in 1895 had a profound impact on science in general and on the practice of medicine in particular; not the least of its revolutionary effects was felt in the field of diagnosis. A new page in the history of medicine was written with that epoch-making discovery. The writing on the first pages may have been hesitant and irregular, but here and there, even during the first few years, can be observed broad, bold strokes that were prophetic of the advances that were to come.

The opinions as to the usefulness of Röntgen's rays in medical practice among the investigators and authorities in medicine in 1896 varied from extreme skepticism to surprising optimism. Indeed, it is a remarkable and astonishing phenomenon that the possibilities of x-ray diagnosis were so quickly and enthusiastically received. Contemplating the natural and beneficent conservatism which most medical men exhibit toward any new departure in medical science, one may well inquire into the reasons for the relatively rapid manner in which x-rays were applied to medical diagnosis. Within one month after the announcement of the discovery of a penetrating radiation which affected a photographic plate, patients were already being examined by this means. Experiments were being undertaken for improvement of equipment and technic, and efforts were even then under way to provide a means of contrast for demonstration of the soft tissues. It is doubtful whether anywhere in the annals of medical science can such a rapid acceptance of a completely new discovery be found.

The reasons for this unprecedented reception, in so brief a time, of a new medium for diagnosis in medicine are not difficult to uncover, and it may be of some interest to review them, for they are equally potent today. First of all, the nature of the discovery was such that the experiments could be readily repeated and the facts demonstrated visually, without delay and without cavil. Fortunately, apparatus such as Röntgen used was readily available all over the world. With a few simple directions it was possible to reproduce immediately the phenomena which he had so clearly described. By its very nature, then, the discovery was demonstrable of proof even to the most skeptical or hypercritical scientific mind. Furthermore, Röntgen had worked out in such detail the salient facts about this new medium that it was relatively simple to understand the potentialities of its application.

In the minds of medical men a new horizon was discovered. The possibility of submitting to visual inspection, in the living subject, structures which hitherto could be seen only in the surgery or on the autopsy table was so attractive—yes, even so exciting—that the impulse toward investigation and experimentation was well-nigh irresistible. Confined to the lesser senses of perception, touch, and sound, with the visual senses restricted to limited use in an indirect way, the medical diagnostician had always labored under great disabilities. The results of his studies were not inconsistent with such handicaps, as any comparison of medical diagnoses with autopsy findings, even during the second decade of this century, will amply attest. The opportunity of performing a veritable *autopsia in vivo* must have been dazzling to the physician who appreciated fully the present limitations of his methods and the possibilities of the new procedure. The importance of visual testimony has been emphasized in the aphorisms of many lands; the physician, like other human beings, places greater reliance upon ocular

perception than on the impressions gained from any other sensory organ. It is no wonder, therefore, that efforts toward improving and utilizing this medium began so early and were pursued with such determination.

The early history of medical progress in the utilization of Röntgen's discovery and much of the literature of the earlier periods has already been splendidly dealt with in a number of articles and books, from which the author has borrowed freely (26, 27, 66, 80, 109). It is not intended, within the limitations of this paper, to review all the advances in roentgen diagnosis over this half century in any detail or with any effort at literal completeness. Rather is it the purpose of this article to point out in broad outline the successive steps which have been taken to bring roentgen diagnosis to its present important place in the medical armamentarium. It seems unnecessary to stress the present position of x-ray examination in medical practice. Suffice it to say that, entirely aside from routine examinations, the scope of x-ray examination is so wide that approximately 80 per cent of patients in hospitals and 70 per cent of those seen in outpatient clinics will be submitted to some form of roentgen study at some period in the course of their illness. Furthermore, routine examination of the thorax is becoming so widely adopted, at least in hospital practice, that eventually all admissions to all hospitals will entail x-ray examination of one kind or another. That such practice may eventually be applied to the gastro-intestinal tract as well is not idle speculation but a real possibility. The importance of x-ray diagnosis cannot, therefore, be overemphasized.

In any discussion of the development of roentgen diagnosis a number of phases must be considered. There is, first, the evolution of x-ray equipment, which is being presented elsewhere in this issue of RADIOLOGY. There is the technic of radiography, also a separate subject in itself. In addition to the developments in these two technical fields, advances in roentgen diagnosis may be considered from the point of view of the evolution of contrast media and their application, the methods of x-ray examination, the roentgen signs of various injuries and disease processes, and the expansion and elaboration of the specific criteria for the x-ray diagnosis of various diseases and their differentiation from normal and other abnormal states. In the latter category come the descriptions of the roentgen anatomy of various organs, both normal and abnormal, and the roentgen signs of specific disorders of these organs.

EVOLUTION OF CONTRAST MEDIA

In the history of medicine there is nowhere a more fascinating chapter than that which relates the story of the introduction and amplification of various contrast media for roentgen diagnosis. It was at once apparent to Röntgen himself and, shortly thereafter, to the medical colleagues to whom he first communicated the results of his research, that the nature of any tissue would determine the degree of its opacity to the x-rays. Because in the early experiments only the bones were clearly visible, and in later studies metallic objects within the tissues were also observed, it was assumed that the efficacy of the method would be limited to the skeleton. For some reason investigation of the thorax was not immediately undertaken, but efforts to make visible the esophagus and the gastro-intestinal tract followed these first halting steps with great rapidity. Early in 1896 metallic sounds were introduced into the esophagus of a cadaver; shortly thereafter lead solutions were injected to make this structure dense enough so that contrast between itself and the surrounding tissues could be achieved. Thus the beginning of a new method of study of the internal organs was initiated.

The development of the use of contrast media in roentgen diagnosis is portrayed to some degree in graphic form in Figures 1 and 2, which have been adapted and elaborated from two figures previously published (173). It should be noted that

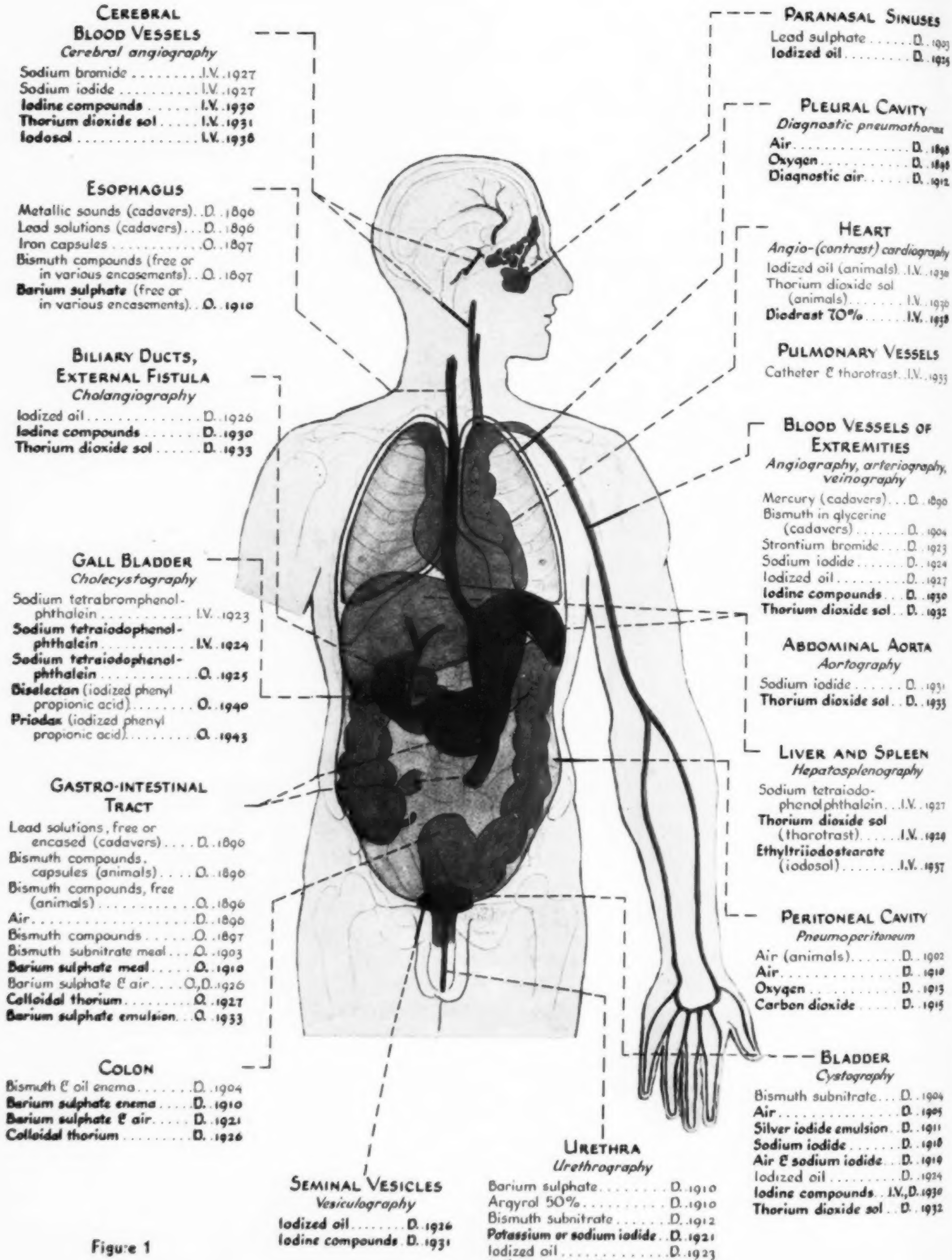
not all of the innumerable variations of the common contrast media have been included in the figures; no doubt some minor contributions may have been omitted. Furthermore, no effort has been made to assign credit to the originator of each procedure. Such details are left to the medical historian, who can best assess the records. By presenting the approximate dates, it is possible to indicate roughly the chronology of the evolution. In the diagrams the obsolete materials are indicated by the light-faced type, while the obsolete procedures are indicated directly. The symbol "D" indicates the direct method of introduction, through a tube, a catheter, needle, or other injection method, while the symbol "O" refers to the oral ingestion of the substance, "I.V" to intravenous introduction, and "I.S" to the intraspinal route. It should be noted that the term "iodine compounds" is used, for purposes of brevity, to refer to the iodine-pyridine derivative (Neo-Iopax) and the iodine preparation (Diodrast), to sodium ortho-iodo-hippurate (Hippuran), as well as to the other organic iodine compounds such as Selectan, Uroselectan, Skiodan, Iopax, Abrodil, Perabrodil, Tenebryl, many of which have related chemical structures, although differing specifically in certain important respects. It may also be noted that Biliselectan and Priodax are trade names for beta(3,5 di-iodo-4-hydroxyphenyl) alpha phenyl propionic acid. The term iodized oil includes Lipiodol, Iodochloral, Iodipin, Campiodol, and other media of similar nature.

It may be well to review briefly the details of the application of the contrast medium principle to the digestive tract. Perhaps the first efforts to make roentgenologically visible the esophagus in the living subject were by means of capsules of reduced iron and small rubber bags containing lead solutions (91). These were not especially successful and it was, no doubt, the original work of Cannon (33) on cats, followed by his work with Williams (221) on man, that gave the real beginnings to gastro-intestinal radiology. It should be noted that Leonard (129), and later Roux and Balthazard (179), followed closely with the same purpose in mind. Rumpel (182) used bismuth in the esophagus in 1897.

Such efforts were fragmentary and left no great impression until Rieder (172) in 1903 formulated the bismuth meal which, with various modifications, remained the standard contrast medium for oral administration in the roentgen study of the digestive tract for some years. At a later time barium sulfate was substituted because of its relative cheapness and more inert character. A great variety of vehicles for the salts were proposed and many used, but there have been no substantial changes in the medium itself since Bachem and Günther (8) described their barium meal. Many variations of the suspending mixture have been instituted, particularly for the more adequate demonstration of the mucosal pattern of the intestinal tract. At present the majority of experienced roentgenologists follow the lead of Cole (52) and others by using a simple water-barium mixture; certain emulsions of barium with gelatine or other colloidal materials are occasionally desirable. The introduction of gas into the stomach, either by injection through a tube, by simple air swallowing, or by chemical reaction such as occurs with Seidlitz powders is sometimes of value, although a simpler procedure is to have the patient swallow a carbonated drink. If barium sulfate is also used, a double contrast is produced, which may be of great value in the diagnosis of tumors of the cardiac end of the stomach.

In the case of the esophagus, many devices have been advocated to procure slow passage and good dilatation of the structure. Thus very thick mixtures, large capsules containing barium sulfate, sausage casings stuffed with barium sulfate mixture, and many other encasements have been advocated. Many of these have an important place under particular circumstances.

The examination of the colon by direct injection of bismuth subnitrate with oil,



CEREBRAL BLOOD VESSELS
Cerebral angiography
Sodium bromide .... I.V. .1927
Sodium iodide .... I.V. .1927
Iodine compounds ...... I.V. .1930
Thorium dioxide sol ..... I.V. .1931
Iodosol .... I.V. .1938
ESOPHAGUS
Metallic sounds (cadavers). .D. .1890
Lead solutions (cadavers) . . . D. .1896
Iron capsules .... O. .1897
Bismuth compounds (free or in various encasements) . . O. .1897
Barium sulphate (free or in various encasements) . . O. .1910
BILIARY DUCTS, EXTERNAL FISTULA
Cholangiography
Iodized oil .... D. .1926
Iodine compounds .... D. .1930
Thorium dioxide sol ...... D. .1933
GALL BLADDER
Cholecystography
Sodium tetrabromphenol-phthalein .... I.V. .1923
Sodium tetraiodophenol-phthalein .... I.V. .1924
Sodium tetraiodophenol-phthalein .... O. .1925
Biselectan (iodized phenyl propionic acid) .... O. .1940
Priodax (iodized phenyl propionic acid) .... O. .1943
GASTRO-INTESTINAL TRACT
Lead solutions, free or encased (cadavers) .... D. .1890
Bismuth compounds, capsules (animals) ..... O. .1890
Bismuth compounds, free (animals) .... O. .1896
Air .... D. .1890
Bismuth compounds .... O. .1897
Bismuth subnitrate meal ... O. .1903
Barium sulphate meal ...... O. .1910
Barium sulphate & air .... O.,D. .1926
Colloidal thorium .... O. .1927
Barium sulphate emulsion. . O. .1933
COLON
Bismuth & oil enema .... D. .1904
Barium sulphate enema ..... D. .1910
Barium sulphate & air ..... D. .1921
Colloidal thorium .... D. .1926
SEMINAL VESICLES
Vesiculography
Iodized oil .... D. .1926
Iodine compounds . D. .1931
URETHRA
Urethrography
Barium sulphate .... D. .1910
Argyrol 50% .... D. .1910
Bismuth subnitrate ...... D. .1912
Potassium or sodium iodide . . D. .1921
Iodized oil .... D. .1923
Iodine compounds .... D. .1931
Iodine in polyvenyl alcohol (visco rayopak) ...... D. .1944
PARANASAL SINUSES
Lead sulphate ...... D. .1903
Iodized oil .... D. .1925
PLEURAL CAVITY
Diagnostic pneumothorax
Air .... D. .1898
Oxygen .... D. .1898
Diagnostic air ..... D. .1912
HEART
Angio-(contrast) cardiography
Iodized oil (animals) . I.V. .1930
Thorium dioxide sol (animals) .... I.V. .1930
Diodrast 70% ...... I.V. .1938
PULMONARY VESSELS
Catheter & thorotrast. I.V. .1933
BLOOD VESSELS OF EXTREMITIES
Angiography, arteriography, veinography
Mercury (cadavers) . . . D. .1890
Bismuth in glycerine (cadavers) .... D. .1904
Strontium bromide .... D. .1923
Sodium iodide .... D. .1924
Iodized oil .... D. .1927
Iodine compounds . . . D. .1930
Thorium dioxide sol . . D. .1932
ABDOMINAL AORTA
Aortography
Sodium iodide ...... D. .1931
Thorium dioxide sol . . D. .1933
LIVER AND SPLEEN
Hepatosplenography
Sodium tetraiodo-phenolphthalein . . I.V. .1927
Thorium dioxide sol (thorotrast) ..... I.V. .1929
Ethyltriiodostearate (iodosol) .... I.V. .1937
PERITONEAL CAVITY
Pneumoperitoneum
Air (animals) .... D. .1902
Air .... D. .1918
Oxygen .... D. .1913
Carbon dioxide ..... D. .1915
BLADDER
Cystography
Bismuth subnitrate . . . D. .1904
Air .... D. .1905
Silver iodide emulsion . D. .1911
Sodium iodide .... D. .1918
Air & sodium iodide ... D. .1919
Iodized oil .... D. .1924
Iodine compounds . . I.V.,D. .1930
Thorium dioxide sol . . D. .1932

Figure 1

in the form of an enema, was first practised by Schüle (189) in 1904. The first mention of the use of barium sulfate in the colon seems to have been in 1911 (86). In 1921, Laurell (128) suggested the reinflation of the colon with air after ingestion of the barium meal; Fischer (71) gave a barium enema and, after its evacuation, reinflated the bowel with air, thus introducing the double contrast enema which has been popularized by Weber (215) in this country. Obviously, the colon is also examined after the ingestion of the barium meal by the oral route.

The institution of a procedure by which contrast substances were introduced into an organ of low density led promptly to further investigation in other fields, notably the urinary tract. The first experiment in this direction was undertaken by Tuffier (207), who introduced into the ureter a catheter rendered radiopaque by impregnation with lead. No effort to inject any fluid substance, however, was made until 1904, when Klose (119) introduced a bismuth suspension through a ureteral catheter with the unfortunate result that the material could not be easily evacuated. In 1906 colloidal silver (212) was first used. Following that time a great variety of media were introduced and discarded until the organic iodine compounds came into general use for both excretion urography and for retrograde procedures. Sodium iodide became the most commonly used medium to be introduced directly into the ureters and kidney pelves; brilliant results in the delineation of the normal and diseased kidney were obtained. So important has roentgen examination become in urologic practice that it now represents a major portion of the urologist's diagnostic procedures.

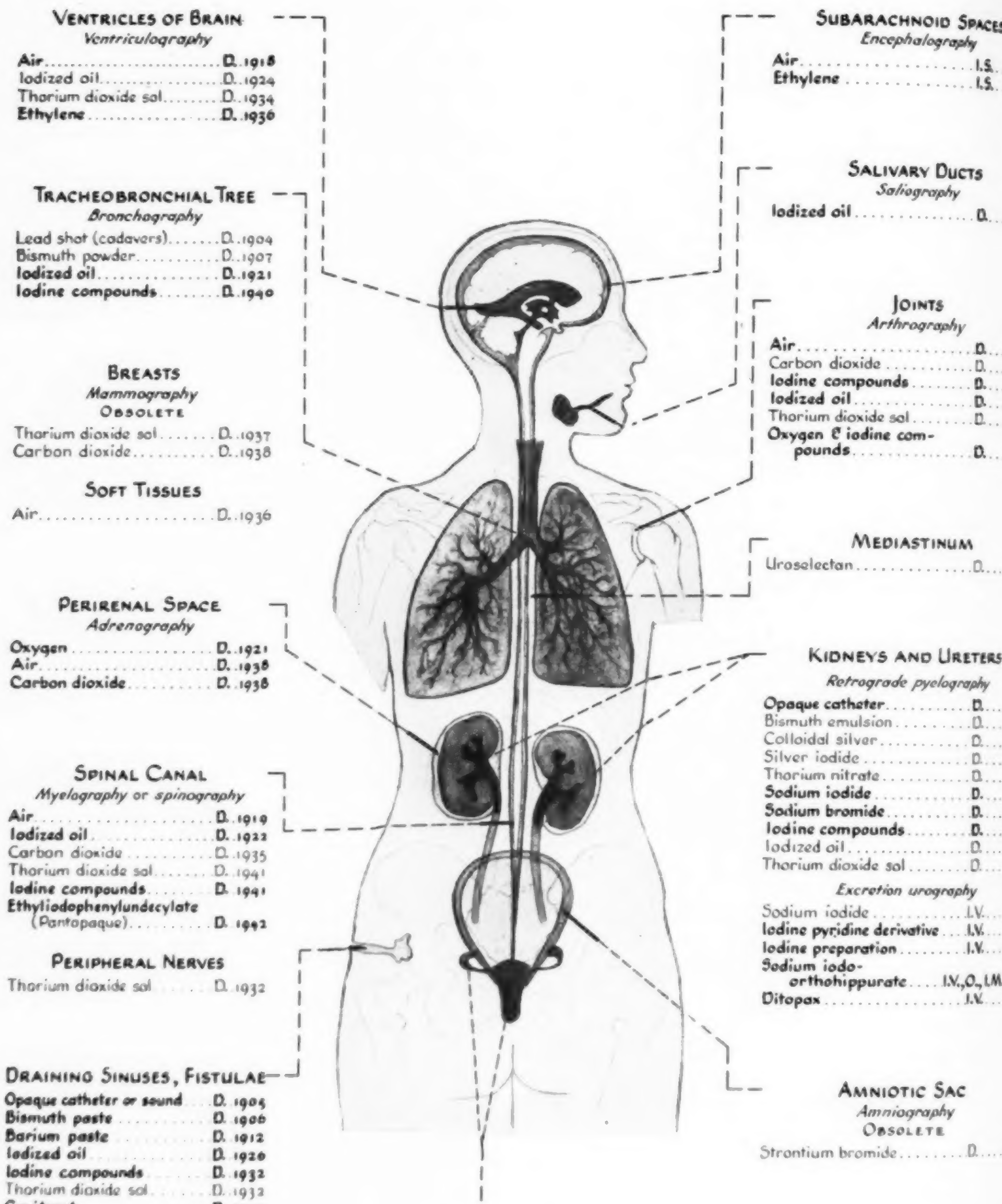
The direct injection of solutions of heavy salts into the bladder followed as a matter of course, and a wide variety of substances came into use for cystography. Here, too, largely through the work of Pfahler (161), the use of air as well as a substance opaque to the x-rays was evolved, and the double-contrast procedure using air and sodium iodide is a standard, important practice today. The examination of the urethra by means of various substances such as barium sulfate and potassium iodide was also undertaken.

It is evident that there was early realization of the salient fact that substances of lower x-ray density than the surrounding medium could be used almost as well as those of greater density. Thus the injection of air into the stomach as a contrast medium was tried very early, albeit with little success. It is notable that therapeutic pneumothorax was introduced about 1898, using both air and oxygen, but it was not specifically instituted for diagnostic purposes until Brauer (25) in 1912 injected air to differentiate the lung from the pleura by means of roentgen examination. Kelling (113), in 1902, injected air into the peritoneal cavity of animals and made direct vision studies. It was Jacobaeus (108), however, who first applied the same principle to man as a method of diagnosis in abdominal conditions and established the procedure of pneumoperitoneum, using air as a medium. Weber (214) used oxygen and was the first to make roentgenograms with this aid. Carbon dioxide was introduced later. Stewart and Stein (199), Carelli and Canévari (34), Sante (185), and numerous other investigators pursued the method, which has, however, fallen into some disuse (140). In occasional situations it is of great value and can be accomplished without danger.

The use of gases as contrast media has

Fig. 1. Development of Contrast Media for Roentgen Diagnosis

A diagrammatic representation of the chronological evolution of the contrast materials used for roentgen diagnosis. Only certain of the body systems and organs are shown in this postero-anterior projection. The name of the procedure, the name of the material, the year it was first used, and the method of introduction are given. Symbols are as follows: D. Direct injection by needle, catheter, or tube. O. Oral route. I.V. Intravenous route. Obsolete contrast media are indicated by light-faced type; media still in use by heavier type. Adapted from Figure 4, Outline of Roentgen Diagnosis (173).



VENTRICLES OF BRAIN
Ventriculography
Air .... D. 1918
Iodized oil .... D. 1924
Thorium dioxide sol .... D. 1934
Ethylene .... D. 1930
TRACHEOBRONCHIAL TREE
Bronchography
Lead shot (cadavers) .... D. 1904
Bismuth powder .... D. 1907
Iodized oil .... D. 1921
Iodine compounds .... D. 1940
BREASTS
Mammography
OBSOLETE
Thorium dioxide sol .... D. 1937
Carbon dioxide .... D. 1938
SOFT TISSUES
Air .... D. 1936
PERIRENAL SPACE
Adrenography
Oxygen .... D. 1921
Air .... D. 1938
Carbon dioxide .... D. 1938
SPINAL CANAL
Myelography or spinography
Air .... D. 1919
Iodized oil .... D. 1922
Carbon dioxide .... D. 1935
Thorium dioxide sol .... D. 1941
Iodine compounds .... D. 1941
Ethyliodophenylundecylate (Pantopaque) .... D. 1942
PERIPHERAL NERVES
Thorium dioxide sol .... D. 1932
DRAINING SINUSES, FISTULAE
Opaque catheter or sound .... D. 1905
Bismuth paste .... D. 1906
Barium paste .... D. 1912
Iodized oil .... D. 1920
Iodine compounds .... D. 1932
Thorium dioxide sol .... D. 1932
Cavitrast .... D. 1942
SUBARACHNOID SPACES
Encephalography
Air .... I.S. 1919
Ethylene .... I.S. 1930
SALIVARY DUCTS
Saliography
Iodized oil .... D.
JOINTS
Arthrography
Air .... D. 1905
Carbon dioxide .... D.
Iodine compounds .... D. 1931
Iodized oil .... D. 1931
Thorium dioxide sol .... D. 1933
Oxygen & iodine compounds .... D. 1933
MEDIASTINUM
Uroselectan .... D. 1935
KIDNEYS AND URETERS
Retrograde pyelography
Opaque catheter .... D. 1897
Bismuth emulsion .... D.
Colloidal silver .... D.
Silver iodide .... D. 1910
Thorium nitrate .... D.
Sodium iodide .... D. 1918
Sodium bromide .... D. 1918
Iodine compounds .... D. 1930
Iodized oil .... D.
Thorium dioxide sol .... D.
Excretion urography
Sodium iodide .... I.V.
Iodine pyridine derivative .... I.V. 1928
Iodine preparation .... I.V. 1930
Sodium iodo-orthohippurate .... I.V., O., I.M. 1933
Ditopax .... I.V. 1941
AMNIOTIC SAC
Amniography
OBSOLETE
Strontium bromide .... D. 1930
UTERUS AND TUBES
Uterosalpingography
Collargol .... D. 1914
Air .... D. 1921
Iodized oil .... D. 1921
Sodium bromide .... D. 1923
Barium sulphate .... D. 1925
Iodine compound .... D. 1931
Thorium dioxide sol. .... D. 1932
Bismuth emulsion .... D. 1939

Figure 2

derived a much wider application in a variety of directions. The injection of air into the perirenal tissues was first introduced in 1921, by Carelli and Sordelli (35) but was later abandoned. Owing to the natural contrast afforded by the perirenal fat, such good delineation of the kidneys could be obtained by modern technics that the addition of a contrast substance seemed unnecessary. New demands, however, for the roentgen demonstration of the adrenal glands have stimulated a revival of the procedure, and perirenal insufflation (adrenography) has thus been re-established for the diagnosis of hyperplasia and tumors of the adrenals.

The most important contribution in the field of low-density contrast media was Dandy's (58) proposal to inject air by needle directly into the ventricles of the brain through a trephine opening in the skull. This was followed shortly by his description (59) of the procedure of encephalography using the intraspinal route. Perhaps the most important agencies in the diagnosis of cerebral lesions were thus established, in 1918 and 1919, and have persisted with but minor changes in technic up to the present time. Ethylene has been substituted for air (153), and improvements in the methods of introduction of the gas, position of the patient, and manipulation of the head have been added, but the fundamental principle has remained.

It is of some interest to observe that as early as 1903, Weil (216) attempted to demonstrate the paranasal sinuses more clearly by injecting lead sulfate. This was abandoned, but the procedure of contrast study of the sinuses was later revived when a more suitable medium was obtained. Similarly bronchography was attempted by Jackson as early as 1907, by the insufflation of bismuth powder. He reported it in 1918 (107) and Lynah and Stewart (136) likewise experimented with this material. Jackson's procedure was not pursued because of the unsatisfactory character of the contrast medium.

Other early and important experiments should be noticed. Hickey (95), in 1904, injected a bismuth glycerin suspension into the arteries of cadavers, this being the first reported attempt at angiography. He also introduced lead shot into the bronchial tree of the cadaver for purposes of anatomical study. Beck (14), in 1906, made a bismuth paste for rendering draining sinuses and fistulae opaque to x-rays.

The formulation of an iodized oil (Lipiodol) by Sicard and Forestier (192) in 1921 was an important event in the onward march of roentgen diagnosis. They did not make any radical departure from the previous methods of introduction of the contrast medium, but their experiment was the first successful attempt to synthesize a compound whose properties would make it particularly suitable for roentgen exploration of internal organs. It was relatively non-irritant and had a high degree of x-ray opacity. While it was absorbed so slowly that it was non-toxic, complete absorption eventually occurred. Its viscosity was both an advantage and disadvantage.

The production of iodized oil permitted the establishment of bronchography (72), than which there is scarcely a more important procedure in the diagnosis of chronic pulmonary diseases. The oil was promptly put into use, also, for myelography (193) and has remained the standard medium for both purposes until very recent years. Of all the contrast media, iodized oil is used in more parts of the body than any other. It has been applied in the urethra, the seminal vesicles, the paranasal sinuses, the uterus and tubes, in external biliary fistulae, and for draining sinuses and other fistulae. It has been used in other organs but not as satisfactorily as are other media.

Fig. 2. Development of Contrast Media for Roentgen Diagnosis

The body systems and organs not exhibited in Figure 1 are shown in this antero-posterior projection. The additional symbol I.S. designates the intraspinal route. Obsolete procedures are so indicated specifically. Adapted from Figure 5, Outline of Roentgen Diagnosis (173).

The success of x-ray examination of the paranasal sinuses, while usually reasonably satisfactory as a result of natural contrast, can in some cases be greatly enhanced by the introduction of a dense material, and iodized oil is admirably suited for this purpose. Reverchon and Worms (171), in 1925, first proposed its use, administering it directly by means of a cannula in the ostium of the sinus. Later Proetz (166, 167) described an inhalation method which had the advantage that it gave a test of function as well. The increased contrast between the cavity of the sinus and its bony wall, together with observations of the time of excretion of the medium, adds materially to the diagnostic findings.

In the same way, iodized oil has been injected into the salivary ducts (159) for the demonstration of occlusion or ruptures, and in such situations it is an occasionally useful device. The urethra has also been examined in this fashion, but here a variety of contrast media have been advocated. Most recently Coe (49) has used a preparation of iodine in vinyl alcohol, called Visco-Rayopak, which he has found even more satisfactory than the others. The seminal vesicles likewise may be outlined satisfactorily by the injection of iodized oil, with consequent improvement in the diagnosis of the diseases of these organs.

Further elaboration of the employment of contrast media in the x-ray diagnosis of diseases of the tracheobronchial tree and lungs seems justified in the light of the importance of this application. Here again, Sicard and Forestier's production of an iodized oil made a new procedure of inestimable value possible. Since that time, many modifications of the material have been made for purposes of bronchography; the only radical departure was Fariñas' (68) description of the use of an organic iodine compound in 1940. The major advances have related themselves to the methods of application, which vary widely even today. The material was originally introduced by means of a laryngeal tube, then by a needle thrust through the cricoid cartilage, then directly through the bronchoscope, then through a catheter placed in the trachea by a variety of means. The introduction of a passive method for the inspiration of the oil into the bronchial tree led to a sharp rise in the usefulness of the procedure, since it could be so employed without instrumentation. At present, one of the two most commonly used methods is the passive procedure; that is, having the patient aspirate the material dropped along the back of the tongue after anesthetization of the pharynx and larynx. In the other method, a catheter is introduced into the trachea or into one of the main bronchi by passing it through the larynx during bronchoscopy or by indirect laryngoscopy. Some efforts have been undertaken to atomize the contrast medium and thus permit it to be inhaled directly without anesthesia or instrumentation. Hickey attempted to effectuate such a method in 1924 but was unsuccessful. An effective method of simpler instillation would doubtless be of great advantage.

Regardless of the method of introduction, the value of bronchography in the chronic diseases of the lung cannot be overestimated (164). It permits a visual mapping out of the bronchial tree of each lobe and the determination of the condition of the bronchi at each point. Bronchography extends the physician's view far beyond the end of the bronchoscope; it permits diagnosis at points well beyond the bell of the stethoscope. The fact is that it accounts in considerable part for the relative infrequency of exploratory operations on the chest. In the diagnosis of tumors and inflammations of the bronchi it is of the first importance. One of the real contributions which has aided materially in permitting the great forward strides of thoracic surgery is this method of visual exploration of the lungs with the thorax intact.

The next step in the unfolding picture of the development of contrast media was epoch-making in that it presented an entirely new method of approach. In 1923, Graham and Cole (81) conceived the brilliant idea of substituting a heavier halogen

for the chlorine in sodium tetrachlorphenolphthalein, a drug which had been found by Abel and Rowntree (1) to be excreted by the liver. Sodium tetrabromphenolphthalein and tetraiodophenolphthalein were made, and it was soon found that the intravenous injection of these substances would give a distinct dense shadow of the normal gallbladder. For the first time, a contrast medium was introduced into an organ as a result of its physiology, and the x-ray examination became a test of function as well as a demonstration of gross anatomy and pathology. This exposition of the possibility of utilizing organ function for the introduction of contrast media opened an entirely new field of endeavor which has not yet been fully explored, while at the same time it served to establish the roentgengraphic examination of the gallbladder on a sound basis. Further experimentation followed, notably by Graham, Cole, Copher and Moore (82, 83), Menees and Robinson (142), Milliken and Whitaker (145), and many others, until the iodinated form was well established as the drug of choice. The oral method was instituted and made successful by the use of various vehicles, and the fatty meal was initiated by Boyden (21) as a test of gallbladder emptying. A host of studies of the normal and pathological gallbladder, of its physiology, of its relationship to the sphincter of Oddi have been the consequence of this original work. Of even greater importance, however, was the stimulus given to further studies in other organs, using similar principles of approach.

In 1940 a newer drug, beta(3,5 di-iodo-4-hydroxyphenyl) alpha phenyl propionic acid, was produced, under the trade name Biliselectan (127) for the roentgen examination of the gallbladder. This has come into wide use in this country under the name of Priodax (65, 90), exhibiting certain advantages over such phenolphthalein compounds as Iodeikon. The newer drug does not produce diarrhea nor toxic manifestations of any degree and it appears to produce a denser gallbladder shadow with more constant absorption on oral administration. It is still not fully tested, and certain difficulties may arise, but it appears to be a very satisfactory medium for this purpose.

In 1923, Rowntree and his co-workers (180) conceived the idea that the urinary tract might be made roentgen-opaque by utilizing its function of excretion. They accordingly made roentgen studies of the kidney and bladder after the intravenous injection of very large quantities of a saturated sodium iodide solution. While the experiment was not highly successful, because of the large amount of a toxic drug which had to be given, it nevertheless pointed the way to a new type of x-ray examination of the urinary tract. Finally, in 1928, Lichtwitz, Swick (202), and von Lichtenberg (131), with the aid of a number of organic chemists, produced an organic iodine compound, the sodium salt of 5-iodo-2-pyridon-N-acetic acid, which was excreted almost wholly by the kidneys and produced sufficient x-ray density to give a clear delineation of the renal pelves, ureters, and bladder. Further experiments resulted in the production of a large number of similar compounds, some having somewhat different properties, but all effective as excretory contrast media. Swick (203) later introduced sodium ortho-iodo-hippurate (Hippuran), which could be given orally or even intramuscularly with some success. Thus a new era in urologic diagnosis was achieved. Without cystoscopy and its attendant difficulties, with little or no risk, adequate roentgen visualization of the urinary tract could be obtained, while at the same time a test of the individual function of each kidney was accomplished.

Excretion urography is the method of choice for the routine examination of the urinary tract, particularly if glomerular function is not seriously disturbed; it is commonly used as a preliminary procedure before cystoscopy or retrograde pyelography is initiated. Furthermore, the same iodine compounds, such as Diodrast and Neo-Iopax, were found highly

useful in other fields, notably angiography, contrast cardiography, and cholangiography. Some of them, such as Skiodan, the mono-iodo-methane sulfonate of sodium, are being used for retrograde pyelography as well.

The liver, spleen, and pancreas remained relatively untouched during the introduction of methods to enhance the x-ray density of internal organs. It is true that Einhorn and Stewart (64) attempted to make x-ray examination of the liver after the intravenous injection of Iodeikon, but as the concentration of the iodine was insufficient within the limits imposed by the toxicity of the drug, their efforts were unsuccessful. In 1928, Oka (156) and Radt (170) began experiments with colloidal emulsions to obtain roentgen visualization of the liver and spleen; they proposed to take advantage of the function of the reticulo-endothelial cells of these two organs, that of ingestion of particulate matter found in the blood. Kadrnka (111) helped to produce a relatively stable colloid with small enough particles so that thromboses or capillary obstruction would not be produced. The material used was a colloidal suspension of thorium dioxide called Thorotrast. The intravenous injection of quantities approximating 0.8 gm. per kilogram of body weight resulted in the production of a fairly dense shadow of both liver and spleen. A fairly exact demonstration of the size, shape, and position of these organs and considerable information as to their internal structure were thus obtained. Destructive lesions, such as tumors which replaced the reticulo-endothelial tissue, would leave defects in the roentgenographic shadow. The diagnosis of metastases, primary tumors, cirrhosis, abscess, and other liver diseases could be determined with a reasonable degree of accuracy.

Unfortunately there are two disadvantages in the use of Thorotrast. Thorium dioxide is radioactive and might, therefore, have deleterious effects. Furthermore, the material remains in the liver and spleen and regional lymph nodes for many years, disappearing very gradually, so that a foreign-body effect is produced, in addition to the effects of the alpha radiation. Extensive studies on animals and on man have been made with equivocal results. If large enough doses are used, most certainly very injurious effects will result. With moderate doses, there is grave doubt that any harm will eventuate. Follow-up studies by Yater, Otell, and Hussey (223) and by Rigler, Koucky, and Abraham (175) did not show any serious after-effects, but the author has observed distinct fibrosis of the spleen with marked diminution in size over a ten-year period. There also occurs some fibrosis of the liver, although without appreciable effect on liver function; distinct fibrosis and necrosis of lymph nodes may likewise be found. Regardless of such findings, it seems inadvisable, except under special conditions, to introduce into the liver and spleen, for diagnostic puposes, a medium which will not be eliminated. There is also the possibility that the material may have a local carcinogenic effect. As a result, the procedure is used very little, although diseases of the liver still remain one of the most difficult problems of diagnosis in the field of internal medicine. The same contrast medium has been used effectively in other examinations, as in angiography, cholangiography, uterosalpingography, ventriculography, myelography, and others. Where it is reasonably certain that it will be eliminated, as in cholangiography, there can be little objection to its use. In the case of angiography, the amount injected is ordinarily sufficiently small to make it reasonably safe.

The reluctance to use thorium dioxide sol for the x-ray examination of the liver has led to further researches in this field. The author and his associates attempted to produce a colloidal suspension of an iodized oil as a substitute for the thorium suspension, but were never able to get sufficient concentration of iodine into the liver of an animal without using enormous quantities of the emulsion, far beyond the danger point. In 1937 Degkwitz (60) pro-

duced a colloidal emulsion, ethyl tri-iodo stearate (Iodosol) which Beckermann and Popken (16) applied to the visualization of the liver and spleen. The principle of application was the same as that for thorium dioxide; namely, the introduction into the blood stream of particulate matter which would be ingested by the reticulo-endothelial cells of the liver and spleen. It differs in that Iodosol breaks down within a few hours and is excreted in the form of sodium and potassium iodide. A recent paper by Olsson (157) gives the present data clearly; unfortunately he also reports some severe reactions, with one death in nine cases. Twenty grams of iodine must be given; this alone is not without serious danger, as it will be absorbed within a period of hours. Furthermore, the colloid is evidently not entirely stable and produces reactions of itself. The problem, of visualization of the liver and spleen is, therefore, far from being solved, although efforts in the direction of Degkwitz' fundamental work on the distribution of colloids may make it possible. This is one of the remaining unsolved problems in roentgen diagnosis.

As shown in the accompanying figures (pages 470 and 472), in almost all of the anatomical structures to be examined there has been a gradual evolution of method and material. The first efforts to examine the central nervous system effectively with the roentgen rays date from Dandy's (58) historical description of the use of air introduced directly into the cerebral ventricles. Later he described the intraspinal injection of air (59), but myelography as such was not well instituted until 1922, when Sicard and Forestier (193) reported apparently innocuous effects from the instillation of Lipiodol into the spinal canal. Used originally for the diagnosis of tumors, its usefulness has been greatly extended since the work of Mixter and Barr (148) and Hampton and Robinson (88) on the x-ray diagnosis of herniation of the intervertebral disk. Some serious doubts having arisen as to the complete harmlessness of iodized oil in the spinal canal and ventricles of the brain, efforts at providing a substitute which would be absorbed or could be removed more rapidly have continued. Air as a medium of contrast was substituted (50, 225, 46) but was never universally adopted because of the difficulty of interpretation of air spinograms. Thorotrast was advocated also (154), but the persistence of the material in the canal and the possibility that it was locally carcinogenic in its effect led to its abandonment. Extensive experimentation by a team of chemists and radiologists extending over a period of years led eventually to a new contrast medium which will, no doubt, replace iodized oil for this purpose. Strain, Plati, and Warren (200) first reported their work with ethyl iodophenylundecylate (Pantopaque) in 1942 and it has since been given extensive clinical trial. The procedure of removing the contrast medium, either iodized oil or Pantopaque, from the spinal canal (125) has added immeasurably to the field of usefulness of myelography.

A method for the roentgen examination of the peripheral nerves was first proposed by Löhr and Jacobi (134) in 1932. They injected thorium dioxide sol along the nerve sheaths and thereby were able to demonstrate the effects of injury, tumors, and other pathological processes. The method has not been widely adopted, although Saito (183) has used it rather extensively.

The x-ray demonstration of the blood vessels by means of contrast media, administered in one form or another, was first projected in 1896, when mercury was injected into cadavers. The same procedure may be used effectively today for the delineation of the arterial system in an amputated extremity. Hickey (95) used a bismuth glycerine mixture in cadavers to study the anatomy of the circulation. The first clinical attempt was made in 1923 with strontium bromide, following which numerous substances were utilized. Dos Santos and Pereira Caldas (186) introduced the use of thorium dioxide sol for demonstration of the arteries in 1931 and

this medium was later employed for venography as well. The various organic iodine preparations are frequently used for this purpose and more recently Iodosol has been utilized by Häussler, Döring, and Hämmerli (87). In selected cases, the roentgen studies of the veins to which Baker and Miller (10) and others (13, 222) have given so much effort are exceedingly valuable, while arteriography is also helpful in the diagnosis of diseases of the extremities (160, 5, 211).

In 1927 Egas Moniz (61) first made a successful demonstration of the cerebral arteries, using sodium bromide; later he achieved the same result with sodium iodide. By injection of the medium into the internal carotid artery he was able to demonstrate deformities and displacements of the vessels incident to tumors and other lesions of the brain. Later he adopted thorium dioxide sol as a medium, while others have used organic iodine compounds, especially Perabrodil. Kristiansen and Cammermeyer (124) and, more recently, List, Burge, and Hodges (133) have delineated the value of arterio-encephalography or cerebral angiography.

While many studies have been made on cadavers and experimental animals to determine the anatomy of the pulmonary vessels and to relate them to the shadows observed in the ordinary roentgenogram, it was not until 1931 that any success was achieved in making such a demonstration in the living human being (62). This was effected by passing an opaque catheter into the median basilic vein under fluoroscopic control. The catheter was then passed into the superior vena cava and even into the right atrium, whereupon a highly concentrated sodium iodide solution was injected; roentgenograms made immediately gave excellent shadows of the pulmonary arteries. While some modifications of this procedure are still being used in experimental work, particularly for measuring the pressure in the right atrium and even in the right ventricle, it has not attained any considerable use as an x-ray diagnostic procedure, no doubt because of the attendant risk and the difficulty of approach.

A much safer and less trying procedure was described by Robb and Steinberg (176) in 1938. They injected a 70 per cent solution of Diodrast into the median basilic vein with great rapidity and made repeated rapid exposures of the heart and lungs. Preliminary measurements of the circulation time permitted a determination of the desirable intervals between the roentgenograms. This method has some practical diagnostic value but is of even greater importance as a means of studying the physiology of the heart and lungs. It offers some aid in the diagnosis of congenital heart lesions and pulmonary artery disease and in the differentiation of vascular masses from mediastinal tumors. A similar method was applied to children by Castellanos, Pereiras, and Argelio García (44), who called it angiocardiography. Much information as to the roentgen anatomy of the heart in health and disease can also be obtained in this fashion, as indicated by the papers of Sussman and his co-workers (196, 84), and in a recent contribution by Miller (144). It should be noted that earlier German investigators had utilized a combination of iodized oil and Thorotrast in animals, and even in one case in man, to demonstrate by fluoroscopic motion pictures the filling of the right atrium. Stewart and his associates (197) likewise made motion pictures of the fluoroscopic image of the living, pulsating heart when filled with contrast medium by the Robb and Steinberg method. The procedure has not yet been followed through to its full promise. It appears likely that an increase in the intensity of the fluorescent image, which will, no doubt, soon be accomplished, may permit much more to be learned from motion pictures of the opacified heart, because in such a manner the individual chambers may be adequately studied.

Using similar methods, in 1929, dos Santos and his co-workers (187) devised a means for the x-ray examination of the abdominal aorta. They plunged a needle

directly into the aorta through the lumbar muscles and injected concentrated sodium iodide solution and later thorium dioxide sol under great pressure. Not only could roentgenograms of the abdominal aorta be obtained in this way but the various branches, as the splenic, celiac, renal, and ovarian arteries, were also rendered radiopaque. Fariñas and his colleagues (69) have further modified this technic by injecting Thorotrast through a catheter introduced into the abdominal aorta through an incision in the femoral artery. Changes in the arteries due to tumors or other diseases can thus be clearly demonstrated.

The usefulness of contrast media in the x-ray diagnosis of diseases of the female generative organs is rather more circumscribed, but here too the effort to produce contrast was begun rather early—in 1914—by Cary (40), using Collargol. Rubin (181) introduced his test for the patency of the fallopian tubes, using air, in 1920 and, about the same time, Heuser (92) produced roentgenograms of the cavity of the uterus and of the lumina of the tubes after injecting iodized oil directly into the cervical os through the vagina. Since then a variety of media have been used, but iodized oil is still the substance most commonly preferred.

A new method for the x-ray delineation of internal organs—cholangiography—was instituted in 1924, when iodized oil was injected into an external biliary fistula and a clear delineation of the major biliary ducts was produced (126). An earlier attempt, with an emulsion of barium, had been unsuccessful (39). Further studies led to Mirrizi's procedure (146, 147), in which the contrast medium was injected into the common bile duct by way of the gallbladder, or directly, while the abdomen was open during operation. By this means it became possible to determine the patency of the ductus choledochus and the presence of stones before closing the abdomen. If a permanent drain were left in the gallbladder or common duct, further observations of a similar kind could be made under more favorable conditions, at any time after operation. Such procedure is now widely used whenever it is suspected that calculi may be present in the common duct. Saralegui (188), using thorium suspensions, made splendid studies of the physiology of the duct. Mirrizi (147) advocates the use of iodine preparations, which in the author's hands have been far more satisfactory than iodized oil and safer than Thorotrast. Many others have contributed in this field (79, 93, 177).

Contrast examination of the joints has been used from time to time. Efforts at the visualization of the synovial membranes and cartilages began in 1905, when Hoffa (101) and others introduced air into joints for purposes of contrast and made x-ray studies. Burman, Tunick and Pomeranz (29) used iodized oil in 1932. Michaëlis (143) and many others utilized the various organic iodine compounds. Oberholzer (155) even used Thorotrast experimentally for this purpose. Finally Bircher (18) advocated the combined use of an iodine compound with oxygen, thus giving a double contrast. The procedure is not frequently used, but in certain cases may be of great value, as illustrated by the review written by Lindblom (132).

As was to be expected, certain procedures for the production of contrast in the x-ray examination of the soft tissues have been abandoned. One of these was amniography, first described by Menees, Miller, and Holly (141). The results of a direct injection of strontium bromide into the amniotic sac in pregnant women to permit visualization of the fetal soft parts and the placenta were often so deleterious that the method was never widely used. More recently Ehrhardt (63) used Iodosol intravenously in animals, finding that it was deposited in the placenta and could therefore identify abnormalities of that structure. The method has not yet been put to clinical trial.

A method of indirect visualization of the placenta by the use of contrast medium in the urinary bladder has been described by Ude and his co-workers (209). They injected air and later sodium iodide in small

quantities into the bladder and were able to recognize the presence or absence of the placenta in the lower uterine segment by the extent of the separation of the fetal head from the shadow of the bladder. A perfectly safe procedure, indirect placentography is reasonably accurate and of the first importance in the early diagnosis of placenta praevia.

Another procedure which has not been fully accepted is mammography. The injection of thorium dioxide sol into the breast (94) for the demonstration of the lacteal ducts, by which means distortion or obstruction by tumors or other diseases could be observed, has not been pursued further because of the inherent dangers. Air and carbon dioxide have also been used, and in one instance iodized oil, but the method has never met with any widespread approval.

Such a recital of accomplishments in the development of contrast media for roentgen diagnosis would scarcely be complete without noting the problems yet to be solved. First and foremost among these is a method for making the pancreas directly visible in the roentgenogram. It is true that in the past decade some progress has been made in the diagnosis of diseases of the pancreas through the medium of blood enzyme determinations and examination of the stools. Furthermore, the roentgen study of the displacements of neighboring organs, especially the stomach and colon, may occasionally be of considerable value; yet the pancreas still presents the physician with one of his most perplexing diagnostic pursuits. In occasional instances, in cholangiograms made after operation, the entire pancreatic duct, including even some of the smaller branches, can be clearly observed. In such cases one is afforded a glimpse into the possibilities of the roentgen examination of the pancreas which is stimulating, albeit not at all satisfying.

It is obvious from the discussion on previous pages that the present status of the diagnosis of diseases of the liver and spleen is far from satisfactory. Here, too, a more harmless but sufficiently radiopaque medium would be of profound value.

A method for enhancing the density of cartilaginous structures or increasing the contrast about them without the necessity of putting a needle into the joint would represent a striking advance. The manipulation by which a "vacuum" is induced in the joint cavity by stretching or twisting of the joint, as reported by Magnusson (138) and others, does produce some contrast, but it is scarcely a satisfactory method for the roentgen demonstration of the cartilages. The risk inherent in the needling of a joint has retarded the utilization of arthrography. It is conceivable that striking improvements in soft-tissue technic may permit visualization of the cartilaginous portion of the skeleton without the addition of a contrast medium.

In some situations the method of application of contrast media could be greatly improved. In ventriculography and encephalography, for example, the present approach, either through trephining the skull or by the intraspinal route, involves some danger and a great deal of distress. The synthesis of a contrast material which, upon intravenous injection, would be excreted through the choroid plexus, thereby enhancing the density of the spinal fluid, would solve many problems in the diagnosis of intracranial and intraspinal lesions. If we were able to apply x-ray examination as frequently to the central nervous system, when minor symptoms alone are present, as we do, for instance, to the urinary tract, there might appear a striking improvement in the therapeutic results.

Many other possible advances in the use of contrast media for x-ray diagnosis will suggest themselves and, no doubt, the years to come will substantiate the validity of some of these suggestions. The great strides that have been taken during the past half century can only indicate advances of a similar order in the future.

METHODS OF EXAMINATION

With its first breath of life, the roentgen method of examination divided itself into

two major procedures; for Röntgen discovered both the fluorescent effect of x-rays on a screen coated with crystals and the photographic effect on a sensitive emulsion almost simultaneously. Not long thereafter Pupin (168) devised a reasonably practical fluoroscopic screen, which much research has brought to the form of today—far superior, yet still imperfect. It is interesting to observe that as early as the second year of the utilization of x-rays for diagnosis there was conflict as to the respective merits of fluoroscopy and radiography. The great advantages of fluoroscopy in a wide variety of conditions, including especially the diagnosis of fractures, were extolled before a meeting of the London Roentgen Society in 1899 (149) while Brown (26) reports Wilbert's criticism of the practice in cases of injury.

Differences of opinion as to the relative position of the fluoroscopic procedure and radiography have persisted to a lesser degree up to the present time. We have passed through a period of controversy in this matter in the field of gastro-intestinal diagnosis which has been resolved in the minds of most radiologists by the sustained conclusion that each agency is supplemental to the other. Despite this, even in recent years, the author has heard one of the most respected elders in our group declare that it would be a great boon if all fluoroscopes were destroyed.

Fluoroscopy is now rarely used for the detection of fractures, although during the recent period of the war-induced shortage of x-ray film, many, no doubt, were tempted to resort to it again. But for study of the dynamic organs fluoroscopy remains invaluable. Holzknecht (104) and his colleagues in the Viennese School utilized fluoroscopy to its ultimate usefulness both in the examination of the heart, lungs, and diaphragm and in the study of the digestive tract. Carman (36) and his associates developed the art of fluoroscopy of the stomach and colon to a brilliant degree. Similarly, many another radiologist acquired a facility in roentgenoscopic observation which seemed to make radiographic studies almost unnecessary. The history of fluoroscopy, particularly as applied to the gastro-intestinal tract, has been splendidly related by Brown (28).

A modification of the ordinary fluoroscopic technic, originated by Moritz (151), called orthodiagraphy, makes it possible to obtain accurate measurements during the course of a roentgenoscopic examination. This technic has been applied principally to the study of the heart but can be used in other regions also.

The physical foundations of fluoroscopy, the advances in the procedure, and some possibilities for the future have been presented by Chamberlain (45).

Conversely, Cole and his associates (52) were convinced that multiple roentgenograms were far superior in value for interpretation of gastro-intestinal lesions; in addition, the method did not carry with it the inherent dangers of the fluoroscopic procedure. Forssell (73) and his followers, as well as many German radiologists, employed a fluoroscope which could be used as a positioning device for proper radiographic exposure while suitable, also, for real fluoroscopic study. Thus both purposes were adequately accomplished. The filming fluoroscope of Templeton and Hodges (204) is the modern equivalent.

Having passed through these various stages, the method of study at present giving most satisfaction to the largest number of radiologists is a judicious mixture of three procedures. Fluoroscopy is used in the study of the thoracic and abdominal organs and for the positioning of the patient for "spot" films; while radiography is used, in addition, for purposes of procuring detail, a permanent record, and the opportunity for unhurried study. In almost all other portions of the body, radiography alone is employed. It is true that fluoroscopy is applied, under special conditions, as an aid in the reduction of fractures, the location of foreign bodies, the observation of the position and passage of opaque tubes. In addition, it has been used to observe contractions of

the kidney pelves and ureters, for examination of the delivered kidney at the operating table to make certain as to the complete removal of stones, to assist in the procedure of myelography with iodized oil both during the introduction and removal of the substance, during bronchography, ventriculography, and in other such special procedures.

Radiography may be applied as a method anywhere in the body. The technics of its employment have undergone changes during the past fifty years which are the results of the development of new equipment and new methods of approach. Thus the introduction of the intensifying screen made a sharp improvement in the application of radiographic examination. Later the invention of the hot-cathode tube and still later of the rotating anode tube permitted even further advances in the art of radiography. The production of the double-coated film resulted in another striking improvement. No doubt Bucky's description of the principle of the moving diaphragm and Potter's application of it to a practical model made the greatest impact upon radiography.

Early in the history of roentgenology, Köhler (122) devised the method of teleoroentgenography especially for cardiac measurements. The procedure of making films with the tube at a great distance has now been adopted for many other purposes. Nevertheless, in fundamentals, the general methods of radiography remain the same.

That the principles of stereoscopy could be applied to radiographic procedures was conceived of by Elihu Thomson in 1896 (206) and Mackenzie-Davidson (137) utilized it as a method for localizing foreign bodies shortly thereafter, at the same time devising a method for viewing stereoscopic roentgenograms. From that time until the present day the stereoscopic process has been modified repeatedly, applied widely, given undue emphasis at times, unwisely deprecated at others. It need not be used routinely but is of great value in certain areas and under particular circumstances.

With the institution of methods of localization of foreign bodies by stereoscopy, by triangulation, and innumerable other modifications, have come systems of mensuration of various structures. Such measuring devices have been applied particularly to the determination of the exact size of the various diameters of the female pelvis which are important from an obstetrical point of view. Thus have been projected numerous procedures varying in complexity, some dependent on stereoscopy (99, 110, 31) and others on distortion corrections by the use of known factors (205, 11). The subject has been reviewed by Snow (194) and others.

The introduction of roentgenkymography by Stumpf (201) and a number of other investigators made a first departure from orthodox radiographic procedure, for here either the film, or a heavy diaphragm before it, is in motion during the exposure, so that it becomes possible to record the movements of an organ on one film. The first efforts of Crane (56) in this direction were most prophetic. In this connection Jarre's (109) description of MacIntyre's effort to produce x-ray cinematographic film in 1897 is worth rereading. The bold and imaginative investigations of that early day make us humble. But roentgenkymography is of a different character in that it can be performed on any patient, with little risk and with relatively little effort. Although its practical application is limited, it may nevertheless be extremely useful, particularly in the diagnosis of certain cardiac lesions, in the differentiation of mediastinal masses, and in the elucidation of abnormalities of motion anywhere. It has proved of particular value in the diagnosis of constrictive pericarditis, myocardial infarction, and calcification of the valves of the heart. Furthermore, studies with the roentgenkymograph have effectuated a distinct increase in our knowledge of the physiology of the heart. One of the striking utilizations of the instrument has been in experimental studies wherein it is desirable to measure the output of the heart

(114). The work of Hirsch (98) and of Scott and Moore (191) and others in this country, on roentgenkymography, especially of the heart, gave impetus to the method.

Another sharp departure from conventional radiography originated with Vallebona's (210) first description of a practical method of radiography of various body planes. This was preceded by the patent of Bocage (20). Ziedses des Plantes (226), Grossman (85), Kieffer (115), Moore (150), and Twining (208) have added materially to the perfection of this technic, which eventually should have a profound effect on roentgen diagnosis, particularly in certain organs. The review of Andrews (6) clarifies the methods and their value. Whether the procedure is designated as body-section roentgenography, tomography, planigraphy, stratigraphy, laminagraphy, the general principle is the same. It consists of a blurring out of certain planes of the body by keeping the x-ray film and the x-ray tube in motion throughout the exposure but maintaining such a relationship between the two as to preserve the sharpness of detail in the plane desired. The impact of this radical change from the usual type of radiography has been less than deserved, probably owing to the expense and time involved. Further experience, particularly in diseases of the chest, in diseases of the cranial and intracranial structures, and in the larynx, will undoubtedly demonstrate that the method is of inestimable value, both for practical diagnosis and as a means of study.

A means of accomplishing the same purpose as is achieved by body-section roentgenography was originally described by Cottenot (55). The method is called serioscopy and consists of the production of two sets of stereoscopic films with the tube shifting in different directions. Superimposition of the films and the shifting of their positions with relation to each other permit the examination of any number of planes, which can be sharpened or blurred out by appropriate changes in the relative positions of the four films.

Finally a combination of photography and fluoroscopy represents an extremely important departure from the conventional types of roentgen examination. Photofluorography, which, in a sense, dates back to the historic experiments of MacIntyre in 1896 (109) and of Bleyer (19) also in 1896, was first projected for mass examination of large numbers of the population, with miniature films, by D'Abreu (57) in 1936. Introduced into this country by Potter (165), the procedure of making a photographic record of the fluoroscopic image on small-sized film has rapidly become the accepted method for detecting lesions of pulmonary tuberculosis among apparently normal individuals. It is unnecessary to expatiate further here upon the history and present application of photofluorography, since it has been so recently described in the monograph by Hilleboe and Morgan (97). It should be noted that it may have a profound effect upon the future of roentgen diagnosis. The increase in routine examinations of various parts throws a great burden of responsibility on the radiologist for the diagnosis of disease at an early stage. While photofluorography, with its advantages of simplicity, relatively low cost, and rapidity of application, is now being applied solely to the thorax, it may possibly be improved to the point where it will be applicable to the gastro-intestinal tract and other organs. Thus, lesions which are so small as to be symptomless will be observed far more frequently than under present conditions and a much greater responsibility will fall upon him who is called upon to interpret their significance.

That the methods of roentgen examination are not static is apparent from the brief recital above. When it is considered that there is a close relationship between the principles employed in roentgenologic study and the science of electronics, it becomes perfectly evident that even greater changes are in store for the future. Probably nothing is more certain about roentgenology than the certainty of profound changes.

EVOLUTION OF DIAGNOSTIC CRITERIA

If progress in the roentgen diagnosis of the various systems had been logical, it might have assumed a very distinctive pattern. The first reasonable step in the development of the roentgen examination of any organ would be the demonstration of the normal roentgen anatomy, followed by a consideration of the common anatomical variations. After this would come the descriptions of the roentgen appearance of the various pathological affections of the organ, their variations and aberrations. Finally there would appear the roentgen signs which would assist in the differential diagnosis of one abnormal state from another. By the very nature of medical experimentation and study, however, no such consistent progression of ideas could be expected. For example, descriptions of the roentgen appearance of traumatic lesions of the bones and of bone tumors were reported some time preceding the detailed delineation of the roentgen picture of the normal skeletal structures.

Nevertheless, a kind of consistent thread can be detected running through the evolution of the roentgen diagnostic criteria of disease. The first steps are often hesitant and groping, as the pathology of a disease process is first recognized in the roentgenogram. The organ is then restudied to determine its normal appearance. Anatomical variations now enter the picture, leading to many false positive diagnoses. Such deviations are clarified and added to at irregular intervals, while definite criteria leading to the recognition of the roentgen signs of the disease are laid down. At about this time the brashness and overconfidence of youth assail the investigators so that the roentgen findings seem to be most specific and are considered to be pathognomonic of the disease. As time goes on and experience produces its usual salutary effect, the simulation of the roentgen appearance by other disease processes of different nature and etiology is revealed, so that the specificity of the signs is no longer valid. Finally, a more conservative point of view prevails and a reasonable interpretation of the significance of the roentgen findings is attained.

Essentially, roentgen diagnosis has consisted in the production of a special type of representation of the gross anatomical appearance of any organ, together with its aberrations under the influence of injury or disease. Added to this are the observations of certain changes in the normal functions of an organ, some of which, also, can be ascertained by means of roentgen examination. Early in the history of roentgen diagnosis, and, regrettably, too much so even today, the findings were looked at in the light of a photographic image, impressed upon the memory. When such an image was again encountered, it was recognized as the picture of a certain organ or a certain disease process. Soon, however, the enormous variations which biological processes always exhibit made it evident that no such simple feat of photographic memory was sufficient; consequently, specific details and characteristic criteria were recorded, classified, and then made into a composite picture. Even such a picture was not always complete; in many instances parts of the tableau were either distorted or missing altogether; but a sufficient number of the elements of the puzzle could be recognized frequently enough to make the identification of the process secure.

From this type of thinking, similar, no doubt, to that which permeates medical diagnosis in general, arose the conception of a typical roentgen picture of a disease process. Unfortunately, however, the term "typical" has too often been interpreted as meaning common. Nothing could be further from the truth, for if by a "typical" picture we mean the presence of all the criteria in characteristic form, it is infrequently encountered. But if we think of "typical" as inclusive of all the details and at the same time bear in mind that most of the cases will exhibit variations and fail to display many of the signs, the conception is most helpful.

In the course of events, many so-called

"characteristic" signs have been found to be fallacious while other findings of greater validity have been observed. From time to time, fresh observations are made upon old disease processes and new roentgen signs are recorded. Likewise, at intervals, new diseases are encountered. As such previously unrecognized pathological entities are uncovered, either at autopsy, by clinical examination, or as a result of roentgen studies, the x-ray findings have been tabulated, assessed, and reassessed until the new entity takes its place among the rapidly growing number of diseases which are recognizable by x-ray examination.

The progression of the events described above is less spectacular than those related in connection with the discovery of contrast media. Progress in the establishment of the roentgen criteria of disease is more plodding, with a great deal of detail in its fabric; accomplishment is, nevertheless, fully as great. In a masterful study, Percy Brown (26) reviewed in considerable detail the development of radiologic diagnosis through the first thirty-seven years of the roentgen era. It would be presumptuous to repeat his splendid analysis. There have been other detailed reviews of more restricted character (174). The *Year Books of Radiology* were begun in the very year that Brown completed his contribution and they furnish a complete survey of the progress in roentgen diagnosis from 1932 onward.

Certain outstanding events, however, in relation to the development of the roentgen diagnosis of a few of the systems may well be described, particularly as illustrations of the pattern of progress outlined above. It should be noted that any such description must necessarily be incomplete and may well do injustice to many investigators. Any such injustice will be entirely fortuitous.

It is not surprising that the first attention to the radiology of the bones and joints related itself almost entirely to traumatic conditions, but experience in this field led to further investigation of other bone lesions. Tumors and certain dyscrasias were readily observed, even in 1896, but a number of years elapsed before the radiographic technic and the knowledge of interpretation permitted any detailed consideration of bone tumors and infections.

By 1901, many traumatic lesions had been examined and Köhler (120) made the first of his many important contributions to roentgen diagnosis, a monograph on diseases of bone. The descriptions of disease processes in the skeleton proceeded apace, naturally arising in connection with clinical and pathologic reports. Hickey's work (96) on the development of the skeleton was of great importance at this time because it pointed to the necessity for familiarity with the normal. Earlier than that, Caldwell (169), Willard (220), Morton (152), Kassabian (112), Monell (149), and others in this country all made extensive descriptions of the roentgen appearance of pathologic processes in the skeleton.

Perhaps the most important publication was Köhler's book (121) on the borderline between the normal and the pathological in the roentgenogram, first appearing in 1910. The phenomenon of a radiologist with a modest office in the relatively small city of Wiesbaden producing so important a monograph may seem surprising. It was the result of painstaking study of the literature and careful observation which so inspired the interest and generosity of his colleagues that he was able to make a magnificent collection of cases with anatomical variations. Köhler's book has passed through many editions, was finally translated into English by Turnbull, and is now rather outdated, but it had an extremely important effect upon roentgen diagnosis, especially of the skeletal system. Anatomy had to be restudied to account for the numerous shadows which were observed in the roentgenogram. Numerous errors were made in the interpretation of such shadows until their innocent nature was established.

The descriptions of the roentgen findings in bone infections and bone tumors proceeded by way of case reports and classifications. The appearance of Kienböck's

(116) descriptions of bone infections and bone tumors and later the publication of Baetjer and Waters' monograph (9) were notable events. The latter authors particularly clarified the field in that they laid down specific criteria for the inspection of roentgenograms of the bones and then attempted to indicate which of these specific findings applied to various diseases. It would be fruitless to attempt to indicate further the progress in such an extensive field. Codman's (48) classical observations and classification of bone tumors is an excellent example of the use to which roentgen diagnosis can be put when interpreted in terms of pathology. Likewise Bloodgood's descriptions of tumors (77) indicated the relationship of their pathology to the roentgen manifestations. Important also was the monograph on bone tumors by Geschickter and Copeland (77), Brailsford's (24) book on the roentgenology of bones and joints, and a similar contribution by Hodges and others (100).

As a specific example of another type of progression, the case of hyperparathyroidism comes to mind. Descriptions of osteitis fibrosa cystica had been made even before the period of roentgen diagnosis. Adequate delineation of the roentgen findings was also recorded, but the etiology of the disease was obscure and therefore the x-ray observations of cysts on the one hand and decalcification on the other were not correlated. Mandl's description (139) of the real nature of the disease in 1926 led rather gradually to a reassessment of these roentgen findings. Hunter and Turnbull's paper (106), followed by those of Ballin (12), Camp (32), and later of Albright (3, 4) and his associates, as well as numerous others, served to classify and clarify the roentgen observations and to correlate them with the blood chemistry. As a result, we now have a reasonably good understanding of the pathogenesis of the disease and, at the same time, are in a much better position to recognize its manifestations in the roentgenogram.

A somewhat different situation pertains in the group of conditions characterized by aseptic necrosis of the epiphyses or the centers of ossification, often called osteochondritis. First described in the hip by a number of investigators as a result of both clinical and roentgen findings, it is at present largely dependent for its diagnosis upon x-ray examination. Furthermore, stemming from the roentgen findings alone, numerous other lesions of similar nature have been discovered. These include such entities as Köhler's disease of the navicular of the foot, Freiberg-Köhler's infraction of the head of the second metatarsal, Osgood-Schlatter's disease of the tibial tuberosity, Kienböck's disease of the os lunate, Scheuermann's disease of the vertebral epiphyses, and many others. The etiology and pathogenesis are not yet clearly understood, but the details of the gross pathology are known; they are so well delineated in the roentgenogram that it is possible to make the diagnosis almost unequivocally from the roentgen findings alone.

The roentgen examination of the neck represents an achievement largely of the past two decades. It is true that at an early period the shadows of the thymus and of the enlarged thyroid were observed. Examination of the pharynx, larynx, and trachea were difficult and unsatisfactory. The publication of Hay's book (89) on this subject opened wide a field of endeavor. This was brought to greater fruition by the studies at the University of Pennsylvania and at Temple University. The addition of sectional radiography made the study of the larynx a practical and highly informative procedure, as pointed out so well by Young (224) and others. The volume by Pancoast, Pendergrass, and Schaeffer (158) covers the field in great detail and with admirable clarity. The roentgen examination of the structures of the neck is now a well established procedure.

The history of the roentgen diagnosis of disease of the gallbladder presents a striking illustration of the difficulties and eventual accomplishments in the roentgen examination of the internal viscera, yet it is sufficiently circumscribed so that it may be reviewed within a limited space. The

progress of events fits well into the general plan of the development of roentgen diagnosis. It is notable that the first observations were experimental in nature, gallstones being studied, after their removal, by Chappuis and Chauvel (47) in 1896. Further experiments of similar nature (78) resulted in some differentiation of the type of biliary calculus which would be amenable to roentgen demonstration. There appears to be some doubt as to whether Beck (15) or Buxbaum (30) was the first to demonstrate a gallstone in a living subject. For practical purposes it was of little significance, as the number of cases in which the procedure was effective was very small; but as a portent for the future, this first clinical experience was of great importance. By 1906, Holland (102) had pointed out some improvements in technic and there appeared to be more hope that x-ray examination would prove to be of substantial value.

A new method of diagnosis was introduced about 1910 by the contributions of Schürmayer (190) and of Pfahler (162), who observed secondary changes in the gastro-intestinal tract. The validity of such observations may well be challenged in the light of our present knowledge, but they represented a trend in observation which lasted for many years. Observations on the errors in interpretation of the various dense shadows found in the right upper quadrant by Holland (103) and Cole (51) led to differential diagnostic procedures to separate gallstones from kidney stones. Improvements in technic at this time led Case (41) to the conclusion, later concurred in by Pfahler (163), that 40 to 50 per cent of gallstones could be demonstrated by roentgen examination. We may now conclude that this was a highly optimistic statement. Even more optimistic were the later papers of Cole and George (53) and of George and Leonard (76), who emphasized the importance of an exacting technic. The monograph which the latter authors published in 1922 detailed both the diagnosis of calcium-containing stones and those which could be observed because of the fact that their density was less than that of the surrounding bile. They also used the secondary effects upon the stomach, duodenum, and colon as evidence of cholecystic disease. Furthermore, they put forth the thesis that the abnormal gallbladder might give a distinct shadow in the roentgenogram, though the normal viscus was invisible. Observations since the advent of cholecystography have indicated the fallacy of some of their data, but their contributions to increased accuracy of diagnosis by a meticulous technic were of the first importance. Their results, apparently proved at operation, were undoubtedly distorted by the well known frequency of cholecystic disease and of gallstones. Several years later Carman, MacCarty, and Camp (38) gave an illuminating discussion of such factors.

In 1924 cholecystography was introduced by Graham and his associates (81); the early history of the procedure has already been reviewed to some degree. Within a few years a new method of approach, which permitted a direct study of the gallbladder and its function, was established. There was discussion as to whether the oral method, introduced by Menees and Robinson (142) and later employed by Whitaker, Milliken, and Vogt (218) should be used or the intravenous route as advocated by Graham and Moore (83), Case (43), Carman (37), Waters (213), and others. The administration of a fatty meal, first introduced by Boyden (21) and later developed by Whitaker and Milliken (217) and by Sosman (195) became an important adjunct in the procedure. It was not long before optimistic statistics were collected to indicate how accurately gallbladder disease as well as gallstones could be diagnosed. Stewart (198) suggested the jejunal introduction of the dye and Sandström (184) devised a method for giving larger doses by dividing it into two portions. Choleretics were administered by Geling (75) to hasten excretion, and Antonucci (7) advised the intravenous administration of glucose.

Changes in the method of preparing the

material in order to facilitate its absorption were brought about. Levyn and Aaron in 1927 (130) suggested the addition of a fruit juice for this purpose. At about the same time Fantus (67) prepared a colloidal suspension of Iodeikon, which seemed to be easier to take and was more constantly absorbed.

While the statistical studies of Case (42), Kirklin (117), and many others indicated a high degree of accuracy, nevertheless various methods to improve technic went forward. There was a percentage of error in the diagnosis of stones of small size. Åkerlund (2), Bernstein (17), and others suggested that roentgenograms be made in the upright position, which permitted a distinct improvement in the demonstration of these smaller calculi.

With the aid of cholecystography Boyden (23) and his associates have carried on extensive studies on the physiology of the gallbladder and of the bile ducts, particularly as relates to the emptying time. Kommerell (123) suggested a study of the common duct during the emptying phase, and Copleman and Sussman (54) more recently have attempted to correlate such findings with disturbances of the physiological balance of the biliary tract.

Benign tumors of the gallbladder were first diagnosed by means of cholecystography by Kirklin in 1932 (118). A number of similar reports have since been made, but the demonstration of a carcinoma of the gallbladder by this means is exceedingly rare.

The gallbladder, no less than any other organ, exhibits anatomical variations which may frequently be mistaken for pathological states. Deformities are not uncommon and are frequently mistaken for adhesions. Boyden (22) described a deformity of the fundus which has been called the "phrygian cap" and demonstrated its innocent character. Bilobed gallbladders, double gallbladders, and absence of the gallbladder have all been described.

In the past few years a new contrast medium for cholecystography, Priodax, has been introduced. The history of this material has already been discussed. It may well replace sodium tetraiodophenolphthalein as the medium of choice.

On the whole, the diagnosis of the gross abnormalities of the gallbladder is on a perfectly sound basis. As in other parts of the body, however, there still remain many unresolved problems related to abnormal functional states of the biliary tract. Such syndromes as biliary dyskinesia should be amenable to roentgen diagnosis. The full possibilities of cholecystography are, therefore, still not completely explored.

Obviously, only a small portion of the field of roentgen diagnosis, as related to the criteria of abnormality, has been touched upon in the recitals given above. It should be noted that there has been no intention to review fully any subject nor to cover the field. The material presented is designed rather to throw some light on the character of the progress which has been achieved during this past half century.

VALUE AND LIMITATIONS OF ROENTGEN DIAGNOSIS

A significant anniversary, such as the one we are celebrating this year, may be a propitious time to desist a moment from our intensive efforts to advance the usefulness of roentgen diagnosis, while we assess the value of what has already been accomplished. It would perhaps be wise to attempt some estimation of the present status of roentgen diagnosis, to determine the place the roentgen method holds in the examination of the various body systems, and to evaluate the reliance to be placed upon the findings obtained. We should attempt to appraise the limitations as well as the range of the x-ray procedure. A simple way to indicate the scope of the method consists in a recital of the indications for its use. The following tabulation, by systems, gives a rough estimate of the general usefulness of roentgen diagnosis in the light of our present knowledge.

Anatomical Parts and Disease Processes to Which Roentgen Diagnosis is Particularly Applicable

1. The *osseous system* including all the bones and joints for:
   (*a*) Congenital defects, dystrophies, disorders of nutrition and metabolism.
   (*b*) Traumatic injuries of all types.
   (*c*) Infections and inflammations which affect the bones or joints, directly or indirectly.
   (*d*) Tumors either arising in the bones or affecting them secondarily.
2. The *head*, including both the cranium and intracranial structures for:
   (*a*) All the diseases included above under the osseous system.
   (*b*) Suspected infections or tumors of the paranasal sinuses.
   (*c*) Inflammations or tumors of the mastoid and internal ear.
   (*d*) Most of the abnormalities of the teeth and jaws.
   (*e*) Suspected foreign bodies, especially metallic, and tumors of the eye.
   (*f*) Intracranial disease, especially brain tumors, brain abscesses, congenital disorders, and the end-results of trauma.
3. The *neck*, including especially the pharynx, larynx, trachea, thyroid, and lymph nodes for:
   (*a*) Foreign bodies, chronic infections, abscesses, and tumors affecting the pharynx, larynx, or trachea.
   (*b*) Enlargements of the thyroid gland.
   (*c*) Calcifications of the lymph nodes.
4. The *respiratory tract*, including the trachea, bronchi, lungs, pleurae, and diaphragm for:
   (*a*) Chronic diseases of the upper respiratory tract.
   (*b*) All acute and chronic diseases of the lower respiratory tract.
   (*c*) All suspected lesions, acute and chronic, congenital or acquired, of the pleurae and diaphragm.
5. The *mediastinum*, including the thyroid gland and thymus for:
   (*a*) Acute and chronic inflammations.
   (*b*) Tumors of all types including the lymphogranulomata.
   (*c*) Enlargements, from whatever cause, of the thyroid, thymus, or lymph nodes.
6. The *cardiovascular system* for:
   (*a*) Those lesions which may cause enlargement or deformity of the heart or abnormality of pulsation.
   (*b*) Calcifications of the heart or its valves.
   (*c*) All diseases of the pericardium.
   (*d*) Congenital anomalies, arteriosclerosis, inflammations, and aneurysms of the great vessels.
   (*e*) Anomalies, traumatic lesions, partial or complete obliteration of the arteries, varicosities, and thromboses of veins.
7. The *digestive tract*, with the exception of the pharynx, but including the esophagus, stomach, small intestine, and colon for:
   (*a*) Anomalies and distortions.
   (*b*) Ulcers, chronic inflammatory conditions, and fistulae.
   (*c*) Tumors of all types.
   (*d*) Traumatic lesions.
8. The *biliary tract*, particularly the gallbladder, but also the remaining ducts under special conditions, for:
   (*a*) All diseases of the gallbladder except during the acute stages.
   (*b*) The biliary ducts at or after operation with external drainage.
9. The *liver and spleen*, but, since the method of examination is probably not entirely harmless, the indications are not clearly established.
10. The *urinary tract*, including the kidneys, ureters, bladder, and urethra for:
    (*a*) Congenital anomalies, traumatic conditions, calculi, tumors, chronic infections, and the end-results of infection and obstruction. The so-called medical diseases of the kidney are less frequently an indication for roentgen examination.
    (*b*) In the bladder, in addition, the determination of the degree of enlargement of the intravesical lobe of the prostate.
    (*c*) Determining the patency of the urethra.
11. The *abdomen in general* for:
    (*a*) Evidences of rupture, from trauma or disease, of any abdominal organ.
    (*b*) General peritonitis with or without abscess formation.
    (*c*) Acute surgical diseases such as acute appendicitis, acute intestinal obstruction, perinephric abscess, or subphrenic abscess.
    (*d*) Miscellaneous tumors and enlargements of the various organs.
    (*e*) Intraperitoneal adhesions.
12. The *female genital tract* for:
    (*a*) Accurate measurement of the bony pelvis.
    (*b*) Determination of the patency of the fallopian tubes.
    (*c*) Tumors and anomalies of the uterus.
    (*d*) The diagnosis of pregnancy and the determination of abnormalities of the fetus or its presentation.
13. The *soft tissues* anywhere in the body, including the breasts. The indications for examination of these structures are not yet fully established. In certain selected cases, notably in subcutaneous emphysema, from gas infection or trauma, in the diagnosis of lipomata, and in certain lesions of the breast, the findings are of great value.
14. *Miscellaneous conditions*, including lesions of the seminal vesicles, the salivary ducts, concrements, calcifications, and foreign bodies, particularly those of metallic origin.

This bare outline of the indications for roentgen examination gives some concept of the manner in which this method of diagnosis cuts across all the specialties and affects the management of many patients. Certain striking omissions from the list emphasize the limitations of the method. Diseases of the skin are not mentioned, and lesions of the breast are a doubtful indication. Many of the diseases of the eye, the nose, the mouth, the pharynx, and the larynx do not demand x-ray study. Likewise, little help will be obtained in the examination of the subcutaneous tissues and the muscles. There is only minor mention of the liver and spleen, while the pancreas, adrenals, ovaries, and salivary glands are scarcely considered, indicating the small part which roentgen examination plays in the diagnosis of diseases of these structures.

Tropical diseases, which have become so well recognized since the beginning of the war, are only moderately affected by roentgen studies. In yaws the changes in the bones can be demonstrated. In schistosomiasis, the enlarged spleen, cirrhotic liver, and esophageal varices can also be delineated by roentgen study. Likewise in filariasis, the liver and spleen changes are demonstrable, particularly if hepatosplenography is used. In the same way the vascular obstructions can be localized by the use of contrast media. In a few other situations the roentgen examination may be of some value but, on the whole, the usefulness of the procedure in this group of conditions is sharply restricted.

An even more searching question relates itself to the general value which may be attached to x-ray examination in any particular portion of the body. A few illustrations of this kind may suffice to indicate the present status. While roentgen examination is undoubtedly extremely accurate in the detection of fractures in all parts of the skeleton, and certainly is the most dependable way of obtaining such information, the results of x-ray examination of the joints, or of any of the cartilaginous structures, are far from accurate. In the ordinary course of traumatic injuries, many serious disabilities may arise because of damage to tendons, ligaments, and other soft parts, which may give little or no manifestations on x-ray examination. A negative report, therefore, in this respect is of little significance.

Even more striking are the value and limitations of x-ray examination in suspected skull fractures. In such instances, great effort is often exerted to execute an adequate roentgen study immediately after the injury. For practical purposes such a procedure is of importance in only two respects: to produce evidence for medicolegal purposes and to rule out a depressed fracture necessitating immediate surgery. Aside from the latter consideration, the roentgen examination adds little to the clinical findings in determining the immediate conduct of the case. The treatment and prognosis are contingent largely upon the extent of brain injury, and this has little compulsive relationship to the presence or extent of a skull fracture. A negative x-ray examination does not rule out cerebral hemorrhage or cerebral injury; a successful demonstration of a fracture does not necessarily indicate serious damage to the brain. Finally, it should be pointed out that even today, with the best technical procedures, a large percentage of fractures of the base of the skull cannot be demonstrated in the roentgenogram.

In inflammations of the extremities without bone involvement, it is clear that the clinical findings are far more important than those adduced by roentgen study. Furthermore, in the early stages of an inflammatory disease of the skeleton, whether it be acute osteomyelitis or acute arthritis, a negative examination is again of no significance. There are definite reasons for the failure of the roentgenogram to record bone infection in its earliest stages. It is conceivable that improvements in technic may vitiate some of these factors. Nevertheless, at present it is important to appreciate such limitations of an otherwise useful

method. When seven to fourteen days have elapsed from the onset, in the subacute stage, the results of the roentgen study assume great importance. The exact location, extent, nature, and severity of an inflammatory lesion of the bone may then be ascertained; the information acquired is invaluable, but for early diagnosis of bone infection one cannot depend to any great extent upon the roentgen study.

In appraising the emphasis which should be placed upon the x-ray findings in lesions of the thoracic organs, a few outstanding examples may be cited. Certain diseases, such as acute bronchitis, milder cases of chronic bronchitis, and the early stages of bronchial asthma, may be present without any roentgen manifestations whatever. In contrast to these, lobar pneumonia may be detected within six hours after its onset—in a few cases even earlier—well before diagnostic physical signs are present. Such a disease as pneumoconiosis can scarcely be recognized in its early stages by any other means.

In the diagnosis of pulmonary tuberculosis, the significance of negative and positive findings is of grave importance. It is very unusual to find symptom-producing pulmonary tuberculosis, of the ordinary chronic type, without positive roentgen findings. In such cases, therefore, assuming an adequate, well executed, well interpreted roentgen examination, a negative picture is of great significance. There are, no doubt, some exceptions to this rule, but they are so infrequent that the dictum may be safely followed. In the case of the more acute types of pulmonary disease, such as acute miliary tuberculosis, the rule does not hold, for severe symptoms may be present for as long as six weeks before the findings become sufficiently characteristic to justify a definite diagnosis. A negative finding in such a situation is of little value. Furthermore, a negative roentgen study, does not exclude pulmonary tuberculosis when there are no symptoms. During the routine examination of the chest of apparently normal individuals it is easily possible for a focus of tuberculosis to be present but so undeveloped as to escape roentgen detection. A period of as long as twenty weeks may elapse after exposure to tuberculosis before the x-ray findings become unequivocally positive.

The significance of positive findings varies much more greatly, depending upon the nature of the findings themselves. Despite many errors in the roentgen diagnosis of pulmonary tuberculosis, the changes observable in the roentgenogram are second only to a positive sputum in the final diagnosis. The findings are almost invariably definite before any symptoms have appeared. In a great many cases, however, the changes which are visible are not specific; the roentgenologists must therefore limit themselves to the statement that abnormality is present but the etiology must be definitely determined by other means.

The relative value of roentgen examination is strikingly illustrated by a consideration of lung tumors. The presence or absence of pulmonary metastases can be determined with extraordinary accuracy by the roentgenographic study of the chest; usually they are evident long before there are any symptoms or physical signs. In many cases the shadows are so specific that little doubt need be entertained as to the nature of the lesion. In other instances, of infiltrative metastases and very small lesions, there may be some doubt as to the nature of the process present, although the findings themselves are perfectly apparent. Metastases to the lungs, of such a nature as to be almost perfectly characteristic, have been observed even though the individual lesion was no larger than 3 mm. in diameter.

The situation presented by the roentgen diagnosis of primary lung tumors is in sharp contrast to that of metastatic deposits. In a small percentage of cases the patient may have symptoms without any x-ray findings whatever. In the vast majority some roentgenologic findings will be obtained if a thorough roentgen study is made, but the nature of the process may not be apparent. A complete examination,

including fluoroscopy, roentgenography in several positions, bronchography, and possibly even body-section roentgenography, may give definite findings, but despite all possible procedures the changes may mimic most completely a variety of other conditions. Primary carcinoma of the lung simulates tuberculosis, pulmonary abscess, bronchiectasis, benign adenoma of the bronchus, and metastases. On the other hand, to make matters even more complex, atypical inflammatory lesions may closely resemble bronchiogenic carcinoma. Not infrequently a diagnosis of primary bronchiogenic carcinoma has been made in the presence of an atypical perihilar tuberculosis. It should be emphasized, nevertheless, that the roentgen study is of great value in the recognition of primary lung tumors. Frequently it is the only effective means of diagnosis. When the roentgen changes are assessed with all the findings, they add immeasurably to the possibilities of early diagnosis of this serious disease. Nevertheless, the accuracy of the method is far greater in the metastatic than the primary lung tumor.

Diseases of the heart also serve as an apt illustration of the differences in the value of roentgen examination in various diseases. Most, although not all, of the congenital defects, well established valvular lesions, and cases of moderately advanced hypertensive heart disease will manifest themselves in the roentgenogram by distinctive changes in the size and contour of the heart. It is not always possible to interpret these in terms of the exact nature of the cardiac disease, but findings of some type to indicate an abnormal heart will be obtained. To the contrary, such serious diseases as coronary sclerosis and coronary thrombosis, in a great many instances, fail to give any evidence whatever of their presence even with the most searching roentgen study. It is true that in some cases roentgenkymography may assist in determining the presence of a myocardial infarct, but the accuracy is still on a low level and little dependence can yet be placed upon this method of examination.

A few more examples in the field of abdominal diseases may further emphasize the importance of an appreciation of the possibilities of roentgen examination. There is unquestionably no more important procedure in the diagnosis of organic disease of the gastro-intestinal tract than the x-ray examination. Particularly in the recognition of the serious, death-dealing lesions of the stomach, such as ulcer and carcinoma, the barium-meal study is the criterion for accurate diagnosis. But the great majority of patients who complain of gastric symptoms have neither of these lesions. A negative roentgen examination of the stomach, therefore, providing it has been done competently, only justifies the physician in telling the patient he has no serious disease. The vast and relatively unexplored realm of the gastric neuroses, the functional disorders of the stomach, and even the acute and chronic non-ulcerous inflammations, is relatively little affected, diagnostically, by roentgen study. To a limited extent, the same is true of the remainder of the digestive tract.

Diseases of the gallbladder and urinary tract lend themselves to an even more accurate estimate of the value of roentgen examination. It is reasonable to conclude, for example, that at least 90 per cent of the patients who exhibit a normally functioning gallbladder on cholecystography have no appreciable disease of that organ. Possibly the percentage is even higher. Furthermore, with cholecystography well done, the absence of a gallbladder shadow or the presence of stones is indicative of a pathological process in at least 95 per cent of the cases.

In a patient suspected of having a kidney stone, what is the significance of a negative roentgen examination of the urinary tract, providing intravenous urography has not been used? The answers to this question will vary to some degree, but in all likelihood not more than 10 per cent of upper urinary tract stones will fail to be manifested by good roentgen studies. Probably, not more than 3 per cent of upper urinary tract stones are non-opaque

to x-ray examination, but, owing to other errors which enter into the average type of roentgen study, 10 per cent is a fair figure. Here again negative findings do not exclude the presence of a kidney stone, although they render it improbable. It is more important that a simple roentgenogram may fail to give any indication whatever of a severe pyelitis, pyelonephritis, tuberculosis, tumor, or any of the glomerular or sclerotic lesions of the kidney. The addition of excretion urography or retrograde pyelography will obviously reduce appreciably the percentage of error. The use of a contrast medium will permit the diagnosis of some of the lesions, such as pyelitis and pyelonephritis, tuberculosis and tumor, but moderate degrees of glomerulonephritis or arteriosclerotic kidney may be present without any very appreciable effect.

A similar analysis could be applied to the whole gamut of roentgen diagnostic procedures. One somewhat consistent rule runs through the whole story—a negative roentgen examination is much less significant than a positive one. This, however, is not always true, as in the case of pulmonary tuberculosis described above; likewise, in osteogenic bone tumors negative findings are of great significance. On the positive side it should be noted that, in general, the roentgen examination is an excellent method for demonstrating the presence of an abnormality. Frequently, however, it is much more difficult, occasionally impossible, to determine accurately the nature or etiology of a lesion. Again there are many striking exceptions, particularly illustrated by the osteogenic bone tumors, mentioned above. Here the roentgen examination is not only the most accurate method of establishing the presence of a tumor but also in determining its nature. On the whole, however, in many cases, all of the clinical findings must be weighed with the roentgen diagnosis to arrive at a correct conclusion as to the exact character of the disease process affecting the patient.

By his immortal discovery Röntgen has afforded the medical profession an instrument of incalculable worth in the diagnosis of disease. To use it well, nothing is of more importance than the knowledge of its possibilities and limitations.

THE FUTURE OF ROENTGEN DIAGNOSIS

Nothing in the realm of writing is more hazardous nor requires greater temerity than the attempt to glimpse the future. Nevertheless, at this point in the history of roentgen diagnosis, a half century after the discovery which made it possible, no great harm will be done by casting some type of prophetic glance into the near future of this method of procedure.

So far as seems possible to determine at the present time, roentgen diagnosis will continue to expand in scope and function. The discovery of a biological test for cancer, for example, might appear, at first glance, to vitiate some of the need for x-ray examination. As a matter of fact, nothing could be farther from the truth. Even if a biological test should indicate the presence of neoplastic disease somewhere in the body, it would still be necessary to localize the tumor and to determine its extent and limitations in order that therapy might be applied. In the same way, it has been suggested that the development of chemotherapy to its fullest potentialities may cause a sharp limitation in the necessity for roentgen examination. There is a grain of truth in this contention, as witness the diminished number of roentgen examinations of the mastoids during the past few years. Likewise, when chemotherapy is developed to the point where it may act as a preventive of certain inflammatory diseases such as pneumonia, for example, the necessity for roentgen examination of the lungs may be diminished to a degree. On the other hand, the ability to treat a disease effectively renders more imperative its early diagnosis. For this reason every means within our power must be exerted to make the diagnosis promptly and effectively, so that the therapy may be applied before serious damage occurs. The best illustration of this can be afforded

by the advances in thoracic and gastric surgery. Twenty years ago the average physician was so pessimistic about the outlook in cases of gastric or pulmonary carcinoma that he put forth no particularly strenuous effort to make the diagnosis certain; x-ray examination was often neglected in such instances, simply because of the feeling that it would do no good. At the present time the converse is true. The ability to cure malignant tumors of the lungs or stomach, if discovered at an early stage, has led to an intensive search for patients who have symptomless lesions. Thus routine fluoroscopic and radiographic examination of the chest is practised in the hope that small, symptomless carcinomas of the lung will be uncovered. Selected groups of patients, such as those with pernicious anemia or with achlorhydria, are subjected to routine roentgen examination of the stomach to discover small symptomless carcinomas which might be amenable to surgery.

Another factor in the usefulness of roentgen examination which may well affect the practice of roentgenology in the future is the increasing age of the population. The diseases which affect older persons are notably of such a character as to require roentgen examination. The increased incidence of tumors, which will undoubtedly occur as the population ages, will mean a sharp rise in the number of x-ray examinations which must be made per capita. The same is true of the increased incidence of chronic pulmonary disorders, chronic cardiac disorders, chronic arthritis, etc.—all of the diseases which comprise that vast accumulation called geriatrics.

Searching for light in dark places, the physician has been led by his ingenuity and inventiveness toward more and more visual instruments. Just as the x-ray examination is attractive because of the indirect visual picture it gives of the gross pathology of any organ, so the direct inspection of a structure is even more informative. During the past few decades, therefore, there have been amassed an amazing number of "scopes" of various kinds and description. All of these are, in a narrow sense, competitors of the roentgen method. In a larger sense, they supplement or complement the roentgen examination. Up to this time, at least, the institution of a direct visual approach to any structure has not resulted in any diminution of the necessity for roentgen study of that structure. On the contrary, in some instances, as in the case of the larynx, the roentgen method of examination has grown in usefulness concomitantly with the development of direct inspection. Where roentgen examination is at best difficult, the development of an accurate visual method may tend to diminish its importance. In the lower segment of the rectum, for example, where x-ray studies are usually unsatisfactory, adequate proctoscopy is no doubt superior in value.

A review of such procedures and their relationship to roentgen study may be of some interest. The development of adequate roentgen studies of the neck, particularly since the advent of body-section roentgenography, now offers useful additional information to the laryngologist, despite the most expert and careful direct laryngoscopy. The extent and distribution of a tumor, its infiltration outside the larynx proper, the involvement of neighboring structures, and other information of a like character can be furnished by x-ray examination although not obtainable with the laryngoscope (224).

In the case of the bronchial tree the problem is somewhat similar. What bronchoscopist would wish to do bronchoscopy without first having an adequate roentgen examination of the chest? In addition, in a great many instances, bronchography with iodized oil supplies information unobtainable in any other way.

The esophagus is even more amenable to roentgen study, as this can be so simply executed that diagnostic esophagoscopy is limited largely to obtaining biopsy material for final confirmation of the diagnosis or to investigation of the obscure case.

In recent years gastroscopy has likewise come to have considerable popularity.

Here, as is also the case with regard to bronchoscopy and esophagoscopy, the procedure is far more difficult and trying for the patient than x-ray examination. Furthermore, it is not nearly so universally available. On the whole, too, direct vision within the stomach is very circumscribed. In many situations, particularly for the diagnosis of gastritis, determination of the cause of hemorrhage from the stomach, and the detection of small tumors, the gastroscope is invaluable and may well be necessary in addition to x-ray examination. On the whole, however, gastroscopy is only a valuable supplementary procedure to the roentgen study. It should be undertaken whenever possible, and the findings obtained correlated with the x-ray findings, but gastroscopy should in no wise be thought of as a substitute for roentgen examination.

Examination of the thoracic cavity with the thoracoscope is largely a therapeutic procedure, and its applicability is so uncommon that it has no appreciable effect upon roentgen studies. In the case of the peritoneal cavity, however, the endoscopic examination is attaining considerable importance as a diagnostic procedure. Still not widely used, it may, in fact, increase the necessity for roentgen examination, if the procedure of Horan (105) becomes generally useful. He introduces a needle into the gallbladder under the guidance of the peritoneoscope and then injects a contrast medium so that cholangiography may be done without the ordinary surgical approach and without having a drainage tube in the biliary tract. By means of peritoneoscopy, it is possible to observe changes on the surface of the liver, such as metastases, cirrhosis, and other lesions; biopsy of the liver is also feasible. The development of biopsy methods reduces somewhat the importance of x-ray examination.

Both cystoscopy and urethroscopy occasionally make x-ray examination of the respective organs unnecessary, but again the over-all view obtained by cystography or urethrography is indispensable, so that roentgen studies are highly desirable.

As stated above, proctoscopy, and in many instances sigmoidoscopy, may furnish information as to the mucosa of the lower bowel which is superior to that obtainable by roentgen examination. The segment of the bowel which it is possible to inspect by this means, however, is small, so that x-ray studies must always be undertaken as well.

Generally speaking, the pursuit of an exact diagnosis is difficult enough in most situations so that every means at our command should be employed to its fullest extent. In the realm of the healing arts there should be no rivalry between systems; on the contrary, every reasonably fruitful procedure should be undertaken and the findings correlated to permit a logical conclusion.

In considering the changes in roentgen diagnosis in the future, probably the most important of all will lie in the field of methods. It is safe to predict that great advances will be made in the next decade in both fluoroscopy by the ordinary means and in photography of the fluoroscopic image. The probability is strong that an electronic method of enhancing the intensity of the fluoroscopic image will become a practical device within the next few years. When this occurs, fluoroscopy may be increased enormously in its value and scope and consequently there may be a rather striking change in the methods of roentgenologic practice.

With the efficiency of the fluorescent screen greatly enhanced, the amount of energy applied may be diminished and the danger from fluoroscopy thereby appreciably reduced. As a result, it may be possible to use fluoroscopy to a much greater extent than at the present time. Furthermore, it may be feasible to change the nature of the crystals used so that more detail will be visible. To the great advantages that fluoroscopy now has in its dynamic character, in the ability to rotate the patient to almost any angle, and in the possibilities of manipulation, will be added some, at least, of the detail which now is available only in the roentgenogram. Changes in the visual image scheme in the

fluoroscopic room may make fluoroscopy a much more pleasant procedure under much lighter conditions. The possibility that the television principle may be applied to fluoroscopy is not too remote; if that were to become true, many of the hazards and unfortunate side-effects of the procedure might be eliminated.

The possibilities of cinematographic fluoroscopic film would no doubt be enormously enhanced by changes in the character of the screen itself and, especially, by amplification of the illumination. It does not seem at all impossible that a motion picture of the fluorescent image may be obtained in almost any case with very little effort. This would permit one of the most desirable means of diagnosis; namely, the careful, leisurely study of the fluoroscopic findings after completion of the examination. Far better consideration might be given to all of the findings if they were enlarged and recorded graphically upon a motion-picture screen.

Improved photographic media together with improved equipment of other types will without doubt permit radiography of much better detail, even of the deeper structures. This may possibly permit us to make earlier diagnoses of metastasis to the spine, for example, a lesion too frequently invisible in the ordinary roentgenogram of today. Similarly, changes in the soft tissues which denote acute osteomyelitis in its earlier stages may become apparent. Soft-tissue radiography will in all likelihood be improved to a large extent during the next decade; such changes may lead to an earlier diagnosis of bone tumors or osteomyelitis and to the diagnosis of many soft-tissue lesions hitherto untouched.

The further development of body-section roentgenography and other methods of a similar character may well give us the answers to some diagnostic problems, particularly in the skull, the spine, the abdomen, and the chest, which still escape us. There is no doubt that body-section roentgenography is still short of its ultimate possibilities; the development of equipment which would permit localization in a simple way, so that a smaller number of roentgenograms would suffice to demonstrate the exact plane of the lesion, would make this a more practical procedure. It would doubtless aid in the diagnosis of many abnormal processes which are now difficult to demonstrate effectively.

The question as to whether better differential diagnoses can be made than at the present time is much more problematic. It would be a great boon if, for example, methods were devised to permit accurate differentiation of lesions in the lungs, so that there would be less doubt as to whether a lesion were tuberculous, pneumonic, or neoplastic. It is exceedingly doubtful that much will be accomplished in this field, in view of the fact that the pathologist, after hundreds of years of study, is still not always able to make an accurate differential diagnosis between such lesions even with the gross specimen in his hand, but must wait for microscopic sections or bacteriologic studies before definitely determining the etiological factor. Nevertheless, some improvement along this line may well occur, however slowly. Likewise in diseases of the stomach, it is conceivable that additional procedures may improve the differential diagnosis.

More detailed views of the stomach and the entire gastro-intestinal tract would be a great improvement and can be expected. As a consequence, the diagnosis of minor mucosal changes such as gastritis or enteritis, will be more accurately made by roentgen study than at the present time.

A revision of our methods of examination in order to learn more about the minor abnormalities in organ physiology would be of great importance and is to be expected, although it may require many more years of study. The ability to detect minor changes in function would lead to a marked improvement in the results of roentgen examination, particularly of the small bowel and the colon. We may be able to devise more exact measurements of functional states than are now possible,

in which event many symptomatic processes, not now recognized as organic, may be more definitely established. There are, obviously, strict limitations to the usefulness of the roentgen method, largely determined by the limitations of what is visible in gross pathologic diagnosis. But the possibility of studying functional disorders roentgenologically may well permit us to go beyond the limits of pathology in the detection of abnormal states.

The recent advances in the use of photofluorography and its application in mass surveys of normal persons may bring about distinctive changes in roentgenologic practice. The routine fluoroscopic examination of many individuals over a period of time has already revealed early symptomless lesions which may be detected in this fashion. Likewise, the results of mass photofluorography are already apparent in the discovery of tumors, inflammatory lesions, and cardiac conditions which were not apparent to the person affected.

A similar type of routine examination, probably more circumscribed, may well be applied to diseases of the stomach. The results of the routine examination of patients with pernicious anemia have been so striking that this type of procedure should be extended. Probably all persons with achlorhydria, or with familial histories of achlorhydria, pernicious anemia, or cancer of the stomach, should be included in groups which should have routine roentgen studies of the stomach.

All of these examinations of apparently normal or symptomless persons must inevitably lead to the exhibition of lesions at an extremely early stage, much earlier, in the mass, than we have been accustomed to encounter. Such a development will lay a much greater responsibility upon the radiologist, who will be forced to make a diagnosis on much less evidence than at the present time. A sharpening of our acuity of observation and of our perspicacity in analyzing the significance of certain shadows must inevitably follow if the fullest advantage is to be taken of these routine examinations.

Better methods for the application of contrast media to organs in which such substances are already in use may be expected. Moreover, the extension of the usefulness of the artificial contrast method to organs which are now roentgenologically invisible seems certain to occur. Such advances have already been discussed.

One more change in the practice of roentgen diagnosis which is highly desirable may well occur in the next decade, as the number of radiologists and technicians assumes a ratio to the population much more in accord with the importance of the specialty. It may be possible to give slower, more careful, individual study to the patient who is sent in for roentgen examination. A rapid x-ray examination of the stomach, for example, often taking not much more than two or three minutes, while it is remarkably effective and accurate in the right hands, does not permit the best type of medical roentgenologic work. The same is true throughout the whole gamut of x-ray examination. In general, the average roentgenologist and the average hospital roentgen department is handling far too large a volume of patients, much too rapidly, considering the importance of the examinations which must be made. The result is that, with the necessity for speed, not all of the facilities at our disposal are commonly used. There is no reason why more body-section roentgenography should not be done, why more examinations of the chest in a variety of positions should not be undertaken, why more patients should not be examined with contrast medium in the joints, in the lungs, or elsewhere in the body. The matter of expense obviously comes into the picture, but some means must be obtained for reducing the tempo of work which the average roentgenologist is compelled to sustain.

Fifty years of unparalleled accomplishment lie behind us. With but few exceptions, the roentgen diagnosis of advanced disease and of gross abnormalities has been firmly established within the limits which are intrinsic in the nature of the process.

But the future is not foreclosed; there is much still to be accomplished. The diagnosis of disease in its incipiency, before it has manifested itself by symptoms, has yet to be widely established. The determination of the nature of many functional disorders, of disturbances in the physiology of organs without obvious pathological change, remains to be clarified. Nothing in the field of medicine is more dynamic or susceptible of improvement than roentgenology.

As we attempt to emulate the achievements of the past half century, it is well within the realms of probability that the answers to many of the remaining problems, which lie within the realm of our present knowledge, will be obtained. Who can foresee what new ideas, what new problems, entirely outside the limited perceptions of today, will present themselves on the hundredth anniversary of Röntgen's discovery?

University of Minnesota
Minneapolis 14, Minn.

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The Development of Roentgen Therapy During Fifty Years

GEORGE E. PFAHLER, M.D., Sc.D., LL.D.

Professor of Radiology, Graduate School of Medicine, University of Pennsylvania, Philadelphia, Penna.

THE FIFTIETH anniversary of the discovery of "the new kind of ray" by Professor Wilhelm Conrad Röntgen demands a survey of the great benefits that were thereby conferred upon mankind. Many of the details in the earlier development of roentgen therapy, preceding 1933, have been so well covered by Dr. U. V. Portmann (50) in the "Science of Radiology" that it would be superfluous to repeat them here. Because of the brevity of this review, also, it will be impossible to do justice to all who have made valuable contributions to the progress that has been made in roentgen therapy.

Professor Röntgen, the modest and true scientist, when he discovered this "new kind of ray" in November 1895, did not immediately proclaim it from the housetop. Instead he was anxious to study the characteristics of these rays thoroughly before making an announcement. Not even his two assistants knew of the discovery. He handed his "preliminary" paper "On a New Kind of Ray" to the President of the Würzburg Physical Medical Society (57) on Dec. 28, 1895, and it was included in the *Annals* of the Society for that year.[1] A friend scientist to whom Professor Röntgen had sent some of his first x-ray pictures loaned them to another friend, who without consent had the story published on Jan. 6, 1896, in the *Wiener Presse*. Immediately thereafter announcements were made throughout the world, in the newspapers and in scientific journals, but apparently Röntgen made but a single public address on the subject, on Jan. 23, 1896, before the Physical Medical Society of Würzburg. The importance of both the physical and medical aspects of his discovery is emphasized by the presentation to this combined society. It was at this meeting that von Kölliker proposed that these unknown or "x" rays be called "Röntgen rays."

Professor Röntgen published two subsequent scientific papers (58, 59) to record his complete investigations, but immediately after the publicity given, without his knowledge or consent, on Jan. 6, 1896, teachers of physics throughout the world repeated these demonstrations in their own laboratories. As a matter of fact, x-rays were being produced in every laboratory of physics where high-tension currents were being passed through Crookes tubes, and some of the photographic effects were recognized even before Röntgen's discovery (Fig. 1), but were not sufficiently investigated. I myself recall seeing the characteristic greenish light of a Crookes tube excited by a static machine in the demonstration of matter or gas in the "radiant state" by Prof. L. G. Cope, in a lecture on physics in 1893, at the Teachers College, Bloomsburg, Pa. This was my first but unrecognized experience with x-rays.

With investigations of the nature, characteristics, and applications of these new rays being carried out all over the civilized world, it is difficult, if not impossible, to establish priority in their use for the treatment of disease. It is equally difficult to give due credit to each investigator who has made a contribution to the extraordinary progress of roentgen therapy during the past fifty years.

Twenty-three days after the newspaper announcement of the discovery of the new rays, the first investigation of their therapeutic value was suggested in a letter to the London *Lancet* by T. Glover Lyon (36), who believed they might have a destructive effect on the tubercle bacillus. His own investigations and those of others soon proved, however, that except in enormous

[1] This paper and the subsequent one are reprinted, in translation, in this issue of RADIOLOGY (pp. 428–435).

and impractical doses the rays have no bactericidal properties. Professor Rieder (who later originated roentgen diagnosis in gastro-enterology) showed as early as 1898 that the beneficial effects of roentgen therapy in infectious diseases were due to the action on the tissues of the host (56).

According to the records of E. H. Grubbe (19) of Chicago, he began x-ray treatment of a cancer of the breast by Jan. 29, 1896 (twenty-three days after the announcement of the discovery in the newspapers), and the next day applied the rays to a case of lupus vulgaris. Grubbe was at that time a manufacturer of Crookes tubes, and the patients were referred to him by two physicians on the staff of the Hahnemann Medical College (Chicago), where his hands were being treated for a dermatitis evidently due to exposure to the rays. Roentgen therapy thus began almost exactly with the discovery of the rays and, so far as is known, was first practised in America.

The interest and enthusiasm aroused by fluoroscopic examinations with the new rays and the absence of any accompanying sensation led to frequent over-exposure and damage, especially to the skin of the faces and hands of the investigators, with a resultant dermatitis, while over-exposure of the scalp in examinations of the skull was followed by alopecia. These effects suggested to many investigators a possible therapeutic value.

L. G. Stevens (65), on April 18, 1896, Feilchenfeld (Lichenfeld) (35) in May 1896, and H. R. Crocker (8) were the first to publish opinions on the "sunburn" or "eczema" caused by the roentgen rays. Early in 1897, T. C. Gilchrist (15) of Johns Hopkins Hospital, Baltimore, collected from the literature 23 such cases; three months later N. S. Scott (61) of Cleveland found 69 examples, and in 1900, E. A. Codman (5) collected 170 cases of roentgen injuries, which proved that the rays had a pronounced biological effect.

The progressive skin effects were recognized by all careful observers relatively early. They are classified, depending upon the degree of effect in the acute stage, as *first degree*, with erythema, pigmentation, and recovery; *second degree*, with erythema, vesiculation, desquamation and recovery; *third degree*, with erythema,

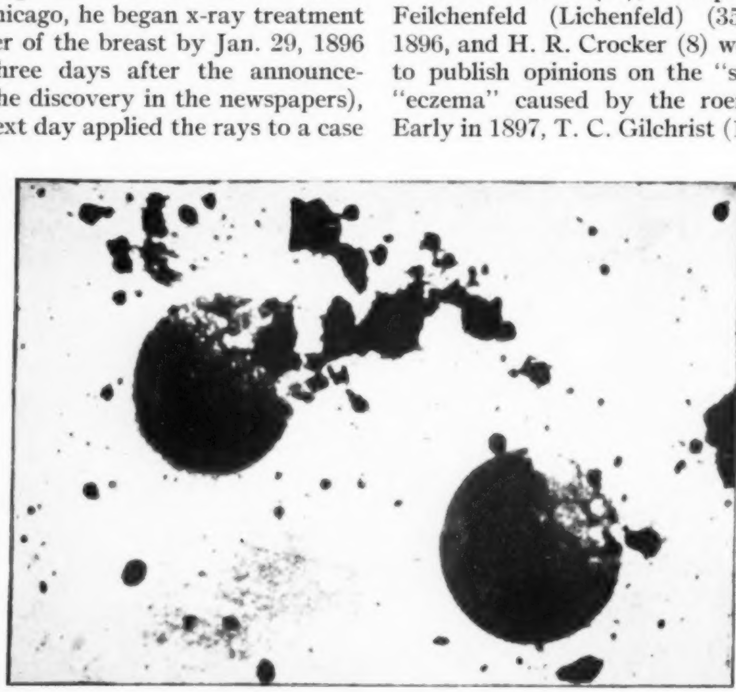


Fig. 1. The first shadowgraph, made accidentally by Prof. A. W. Goodspeed of the University of Pennsylvania while working with the rays from a Crookes tube, February 1890.

vesiculation, ulceration, necrosis, excision, and recovery. In the *chronic cases*, an erythema may or may not be present, but there are atrophy, telangiectasis, splitting of the nails, hyperkeratoses, warts, fissures, and late ulceration, often with the ultimate development of carcinoma.

It was the epilating effect of the roentgen rays which led scientifically and logically to their use in therapy. On April 10, 1896 (three months after the announced discovery), J. Daniel (9) of Vanderbilt University reported the loss of hair from the head of a colleague whose skull he had "photographed with the x-rays." On July 22 of the same year, W. Marcuse (37), in Berlin, published his observations of a patient who had severe skin reactions including epilation following prolonged and frequent exposures to roentgen rays for public demonstrations. Upon the basis of these reports, Leopold Freund (12) used the rays in treating a young girl with a disfiguring hairy nevus. The result was reported to his local medical society on Jan. 15, 1897, just about a year after the discovery of the roentgen rays was announced.

Following the wide publicity given to Freund's report, roentgen rays were used enthusiastically for their therapeutic effect, especially in skin diseases. Priority for their use in specific conditions is given by Kienböck (30) as follows: "hypertrichosis, Freund, 1897; lupus, Kümmel and Schiff, 1897; lupus erythematosus, Schiff, 1898; psoriasis, Ziemssen, 1898; chronic eczema, Hohn, 1898; epithelioma, Sjörgren and Stenbeck, 1899; alopecia areata, Kienböck, 1900; superficial sarcoma, Ricketts, 1900; mycosis fungoides, Scholtz, 1902; leukemia and lymphadenoma, Pusey and Senn, 1903."

At the time of the discovery of the x-rays the essential equipment was available in every well established laboratory of physics, consisting of Ruhmkorff or Tesla coils or the static machine used to produce the necessary high-tension current. The second essential was the Crookes tube. These rudimentary essentials were quickly produced or modified for use in diagnostic work in hospitals and the offices of physicians. The observations on the incidental or damaging biological effects led to the use of the same equipment for therapeutic purposes.

To the modern roentgenologist, this rudimentary equipment must seem absurdly inadequate and, of course, grossly dangerous. The bare clear glass tube was used with no protection either to the patient or the operator. It is not surprising that many of the early workers died from the damaging effects. The volume of the current was very small, so that one heard of exposures of three hours to make a "picture of the hip joint or the kidney." As a result, there were many serious injuries, because the heating of the tube softened the rays and most of them were absorbed in the soft tissues. In 1899, when I began my work at the Philadelphia General Hospital, I was fortunate enough to obtain "a very powerful coil" from Leeds and Northrup Company in Philadelphia, which permitted me to make a "picture" of a hip or a head in eight minutes. At that time, I was interested in diagnosing brain tumors (42) and made two "pictures" of my assistant's head to get a record of the normal in a living subject. In two weeks a complete alopecia of the left side of the head developed, but in three months the hair was entirely restored. It was such experiences that gave some idea of dosage values. We had no voltmeters and no milliampere meters. The voltage was estimated by the length of the point-to-point parallel spark-gap and the intensity of the current, and the penetrative quality of the rays was judged by the appearance of the hand held in front of the fluoroscope. This test led to the loss of the fingers, hands, and even the lives of many of the pioneer workers. The ammeter and the milliampere meter (d'Arsonval) were soon developed to measure the volume of current, and the spintermeter (Béclère) for measuring the spark gap or voltage. The intensity of the irradiation and the dosage were determined by photographic effects (Kienböck) or the darkening effects on barium platinocyanide

Fig. 2. A. Crookes tube, reproduced by Dr. H. C. Rentschler, Westinghouse Electric & Mfg. Co., from designs furnished by Dr. Mutscheller, to represent the type of tube used by Röntgen in his discovery of the rays. Observe that the target was the bottom of the glass tube.

B. One of the tubes used in the Medico-Chirurgical College laboratory by Dr. M. K. Kassabian. This tube, made in 1897, has a cup-shaped cathode and an iridio-platinum target.

The size of these tubes is indicated by the tape measure (in inches). It will be observed that the bulb of the tube shown in B is not more than 3 inches in diameter.

disks (Sabouraud and Noire, Holzknecht, Bordier, Hampson) (50).

The x-ray tube was at the beginning the customary Crookes tube used in the physics laboratory, merely a glass tube exhausted to a high degree of vacuum with simple electric cathode and anode (Fig. 2, A). With a view to increasing the intensity of the rays from a point, the cathode was soon made cup-shaped, directing the beam of cathode rays to a point on the anode consisting of a disk of iridioplatinum (because of its high melting point) (Fig. 2, B). It is impractical here to review every step in the development of the modern therapy tube, and to give due credit to each contributor, but gradually the tube was made larger and the anode heavier, with iridioplatinum central disks in a mass of copper with large supports and external radiators or water-cooled stems to carry off the heat. Elsewhere in this journal[2] details of tube development are described by Dr. W. D. Coolidge, who has played so important a part in this respect.

When large copper anodes came into use, gases given off from the copper reduced the vacuum and the penetrating quality of the rays, which explains many failures in deep therapy in the early days. I commonly used four different tubes to give a single treatment (about 20 per cent of an erythema dose). In spite of this primitive equipment and primitive technic, much progress was made.

During the first ten years after the discovery of roentgen rays, dependence was placed upon larger Ruhmkorff coils or larger static machines to produce a greater volume of high-tension current. (I used a large 16-plate static machine for part of my early therapeutic work.) The vibrating spring interrupters and the electrolytic interrupters limited the amount of current and were a source of much difficulty, while the atmospheric conditions caused much trouble with the static machines. Even in this early stage, Eugene Caldwell, who gave us the Caldwell electrolytic interrupter, had made some progress in the use of valve tubes in the alternating and the three-phase current.

A great step in advance was made by Clyde Snook (1905) when he produced the *interrupterless coil*. This consisted of a motor-driven rotating high-tension switch by which the higher voltage portion of the sine wave was reversed so as to carry the high-tension current into the tube in one direction. This gave a tremendous increase in the possible volume of current and enabled us to shorten diagnostic exposures to seconds, but the prolonged exposures necessary in therapy with the increased volume of current soon over-heated the available tubes in spite of their large size, large anodes, radiators, and water cooling. It was during this period, also with the use of the 16-plate static machine, that I had to use four gas tubes to give a single treatment

[2] See page 449.

and preserve my penetrative values or depth dose.

The next great step in advance was the development in 1913 of the *hot-cathode tube* by our distinguished colleague and friend, W. D. Coolidge (6). This vacuum tube has been improved or enlarged so as to adapt it to many requirements, but in principle it remains the standard today. Basically it consists of a tungsten anode (from the development of ductile tungsten by Dr. Coolidge) and a cup-shaped cathode in which a small coil of molybdenum wire is heated so as to give off electrons with which to bombard the target and produce the roentgen rays. By regulating the amount of low-voltage current passing through the cathode filament, the number of electrons can be controlled and the degree of vacuum or penetrating power of the rays can be controlled and kept constant for any desired volume of current. This constancy in volume and quality of rays has enabled the radiologist to duplicate more closely his own diagnostic and therapeutic results in different patients and at different times, and has made possible descriptions of technic so that similar results could be obtained by others all over the world, with due allowance for variations in biologic response to identical dosage.

BIOLOGICAL EFFECTS

Carefully controlled investigations as to the cause and degree of the biological effects of the roentgen rays began soon after their discovery. Elihu Thomson (66) of Boston, in November 1896, announced his experiment to prove that a dermatitis developed in only that part of the body actually exposed to the rays. Kienböck (29), in 1900 irradiated rats enclosed in metal cylinders to exclude light and electrical effects, thus proving that the effects were the direct result of the rays.

Among the first and best studies of the histologic effects of the rays on the skin were those of A. B. Kibbe (28), of Seattle, Washington, and Gilchrist (15) of Johns Hopkins Hospital, published in January and February 1897, respectively. The latent period and the cumulative effects of the rays on the skin were also recognized in these early days.

The variable effects on different tissues and different types of cells were likewise demonstrated. In 1903, Albers-Schönberg (1) showed that aspermia could be produced in experimental animals by roentgen rays without injury to the overlying skin, which at once proved a striking difference in the sensitivity of different types of cells. This differential effect was established in more detail by Heineke (21), whose report appeared a few weeks later. To him the lymphoid tissues appeared to be especially radiosensitive, and he suggested that roentgen rays might be useful in the treatment of leukemia, without knowing of the beneficial clinical results already obtained by Senn (63), who established definitely the value of deep roentgen therapy.

In 1904, Bergonié and Tribondeau (4) gave a complete histologic picture of the change produced by irradiation in the rat's testicle, showing the focus of attack to be the embryonic structures. They then formulated the law, known by their name, which is the basis of our knowledge of the effect of the rays upon all cells and tissues: "*Immature cells and cells in an active stage of division are more sensitive to radiation than are cells which have already acquired their adult morphological and physiologic characters.*" These observations were supported by similar studies, by Halberstädter (20), of the effects of irradiation upon the ovaries.

IDIOSYNCRASY

Idiosyncrasy has been a debatable subject from the beginning of roentgen therapy. For the most part, it has been discussed from a clinical standpoint. It must be admitted that in the early stages the variable effects observed depended upon lack of instruments for the accurate measurement of the essential factors governing the intensity of radiation, or lack of knowledge of the biological effects to be expected. On the other hand, there can be no doubt that there is a great difference in the effect

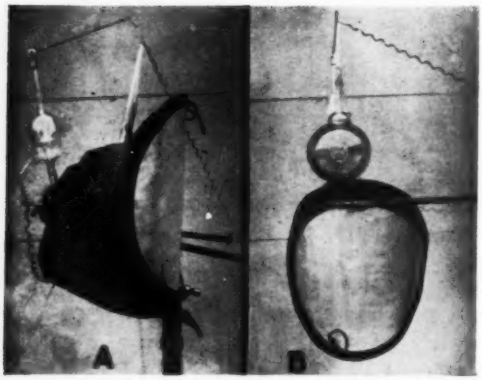


Fig. 3. A. Small aluminum screen with the tube darkened with a black cloth. The holder was an adaptation of a photographic headrest, and in no way grounded, and now definitely used for filtration value. The illustration shows the self-regulating spark gap used to keep the vacuum constant. In B the filter and darkened cloth are turned downward for demonstration of the tube itself from the front.

of measured doses on individuals as observed clinically and as shown experimentally. From the very beginning of experimental work to the present, it has been found that when animals or insects of a known strain and age are exposed in mass to radiation of the same intensity and quality, not all are killed by the so-called "fatal dose," while some fail to survive even a relatively small fraction of the "fatal dose." The difference between the lowest and the highest lethal fatal dose proves the possibility of idiosyncrasy, or extreme sensitivity.

FILTRATION

The injurious effects of the roentgen rays on the skin were recognized by a few men almost immediately after their discovery. Even before this, damage had occurred to men who were making Crookes tubes. Many roentgenologists, and their assistants and patients, however, suffered serious injury before this danger became generally known. Early in the history of roentgenology, these effects were thought by some to be electrical, and grounded aluminum screens were placed between the tube and the patient. In 1899, at the Philadelphia General Hospital, I placed an aluminum screen, 6 × 6 feet and about 2 mm. in thickness, between the tube and the patient and myself, not for protection from the rays but to carry away any electrical currents and as a transparent support for a cloth draped over the tube and the tube-stand. A few months later, this large aluminum screen was replaced by a small one attached to the tube holder, and no longer grounded (Fig. 3). *It must be remembered that at this time open gas tubes were used with no protection*, not even the glass bowl (Figs. 4 and 5). To this device, which gave me some protection in the great amount of fluoroscopic work which I was then doing, I attribute the preservation of my life. I was not only studying the many patients in the Philadelphia General Hospital but I conducted repeated fluoroscopic examinations on interesting cases for demonstrations to the thirty-two resident physicians. The above device enabled me to demonstrate to groups and thus saved time and limited the amount of exposure.

In 1904, Perthes (40) made the first "depth dose" measurements, which subsequently led to the use of filters in Continental Europe. His studies led him to the following significant conclusion: "When irradiating the body, the intensity of the roentgen rays diminishes very rapidly from the surface to the depth; the decrease of intensity in the depth is much less if an absorbing layer, *i.e.*, 1 mm. of aluminum, is placed on the surface of the body." As stated by Portmann, "this work of Perthes led to more thorough investigation of the absorption rate in various media and to the immediate suggestion of the use of homogeneous rays in roentgen therapy as developed within the next few years by F. Dessauer." Perthes' work was not known in America, or at least not to me. My first thought of "filtration" was inspired by the report of the physicist, Walter, in 1905 (69), and I immediately made experimental and clinical investigations which were presented before the American Roentgen Ray Society in September 1905 (43). (Recently I have found a preserved skin from the back of a rabbit used then to test

the value of leather filter. See Figure 6.) My reasoning, as expressed at that time, was based on Röntgen's statement, in his third communication (59), that the x-ray is composed of rays of different quality and that the second layer of any substance absorbs very much less of the rays than are absorbed by the first layer. Walter having confirmed the correctness of Röntgen's original observation, concluded further that "all substances have respectively a selective absorbing power for the rays." Recognizing the above physical laws, namely that each substance has a definite and peculiar absorbing power for the roentgen rays, and that the rays which have once passed through a substance are less likely to be absorbed by a second layer of the same substance, I decided to make a practical application of these principles. At that time the rays which gave us most concern were those that affected the skin when we were treating deep-seated disease. I reasoned that, if the law of selective absorption were correct, the skin would absorb the rays peculiar to itself, and that to remove such rays it was necessary to interpose a filter similar to skin (Figs. 7 and 8). Wet sole leather was thicker but most nearly resembled the skin. This was found effectual, and a dose that would ordinarily cause necrosis of the skin could be given without damage, thereby permitting an increased depth dose and an improvement of clinical results.

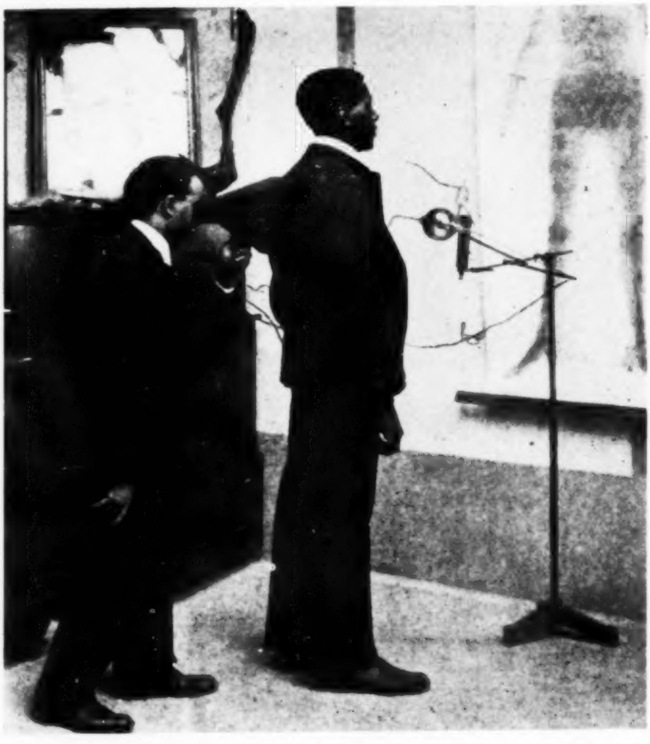


Fig. 4. Equipment and type of tube used at the Medico-Chirurgical College, 1900. Dr. M. K. Kassabian is using the hand fluoroscope with no protection to the patient or the physician. Dr. Kassabian later died from carcinoma secondary to radiation effects.

During the following years, my colleagues throughout this country and in Europe used this filter. We gradually learned, however, that the "peculiar rays"

were not so definite, and the leather filter was abandoned, increasing thicknesses of aluminum being used to remove the softer rays and adapt the quality to the biological effects desired at a given depth.

Gradually our physicists and manufacturers made equipment giving increasing penetration and rays of progressively shorter wave length, permitting a relatively increased depth dose as compared with the effects on superficial tissue. The necessary brevity of this review prevents giving due credit to each contributor or mentioning the detailed steps which were necessary in making these improvements. They are recorded in the mass of roentgen literature which has accumulated during these fifty years.

As higher-voltage rays became available, filtration was also increased. It became evident that after about 4 to 6 mm. of aluminum were necessary (and generally used with low-voltage therapy), the quality of rays or depth value was not greatly increased. At this point copper proved to be better, and after 0.5 to 1 mm. of copper was necessary in so-called "high-voltage therapy" (150 to 200 kv.), tin was found by Thoraeus (67) to be more effectual in improving the quality, as used in the combination Thoraeus filter of tin, copper, and aluminum. This latter filter gives about 25 per cent greater intensity of radiation than the qualitatively equivalent copper filter. As we have gone into the supervoltage field (400 to 1,000 kv. or more), copper, tin, and lead are being used in increasing thickness, and with the hope of developing rays equivalent to the gamma rays from radium.

Fig. 5. Early type of equipment used therapeutically. The "naked" or unprotected tube is being used in the treatment of a recurrent carcinoma of the breast. The patient is holding a lead shield which evidently protects the skin immediately surrounding the lesion, but it can be seen that the hand and the surrounding parts of the body are receiving a very considerable proportion of the radiation. From Monell (38).

While it is true that with higher voltages and increased filtration a greater proportion of rays can be delivered to any given deep point, it would seem that there must be a

limit to the usefulness of increasing penetration. The effectual rays in any given tissue or depth would seem to be those which are absorbed, not those which merely pass through the tissue. It also seems to me that it is wise to use that quality of rays which will have the greatest possible biological effect on the tissue under treatment and at the same time do the least damage to the surrounding tissue, either proximal or distal to the disease, and to essential organs.

The damaging effects on the skin, the demonstration of the value of filtration, and the damage to the gonads and to the body as a whole led naturally to the development of protective devices. The control switches or panels were placed as far away from the tube as possible, first behind lead screens in the same room, then in leaded booths, and finally behind leaded walls in a control room fitted with lead glass windows.

The patient was protected by lead diaphragms, which allowed only the necessary beam of rays to reach him (Fig. 7). (I described such a diaphragm as early as 1903.) In the early days we tried to protect the patient by covering with sheets of lead. This was objectionable, and I developed a variable lead diaphragm which did not touch the patient but still gave protection. A little later, I added lead shields at the edges (Fig. 8). Then, to get better protection, metal tube stands or table supports were developed, holding heavy lead glass bowls. Further protection was later obtained by immersing the entire tube and high-tension apparatus in a grounded metal oil container—on a small scale, the dental outfit (presented by W. D. Coolidge at the meeting of the American Roentgen Ray Society, at Saratoga, 1912), and on a large scale (by the General Electric Mfg. Co.) in the "Maxmar" 400 kv. outfit for supervoltage therapy. "Supervoltage" rays were also developed by the use of cascade tubes, using 1,000 kv., but these required a separate large building (6 stories, Pasadena) and only the beam of rays entered the treatment room. Smaller equipment was then developed, still using 1,000 kv. or more.

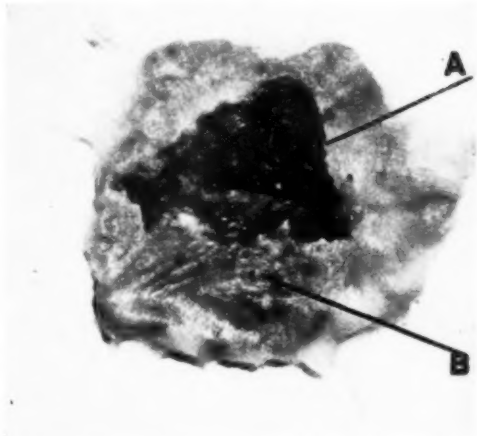


Fig. 6. A portion of the skin of the back of a rabbit used to test the filter value of wet sole leather. The upper half of the exposed area shows (A) deep ulceration. This area was treated with unfiltered radiation for the same length of time, and identically with the area indicated by B. This latter area was protected by wet sole leather which covered half of the lead diaphragm. There is complete epilation but no ulceration, proving definitely the value of filtration. The area treated is not sharply defined because there was naturally slight movement of the rabbit skin during the exposure.

The greater focal skin distance possible with the large volume of roentgen rays from supervoltage equipment probably gives them a great advantage over gamma rays from radium because of the greater depth dose. Much expense is involved, but this is far less than even a fraction of the cost of radium, when account is taken of the volume and intensity of radiation obtained from the supervoltage outfit.

"Supervoltage" (above 200 to 250 kv.) roentgen rays are still under serious and extensive scientific investigation. These rays undoubtedly are of superior value in selected cases but they cannot be used to replace "low-voltage" (50 to 150 kv.) or the "high-voltage" (150 to 250 kv.) rays. These latter types I believe will always be used for the great bulk of work.

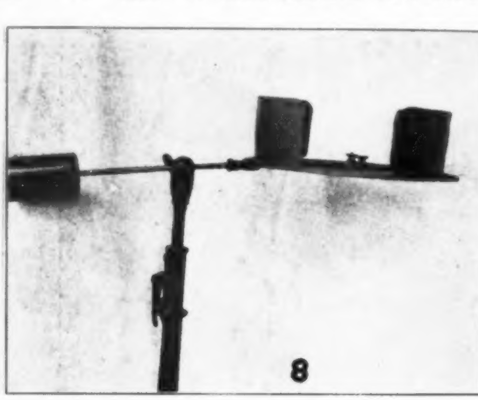
Three principles must be borne in mind: (1) We must use rays of such quality as will be absorbed in great part by the diseased tissue. (2) We must use rays with sufficient penetrating value to reach the

diseased area without doing too much damage to the overlying tissue. (3) We must use a quality of rays and equipment which will permit us to deliver the beam to the diseased area as accurately as possible and inflict a minimum of damage on the surrounding tissue. The lower voltage rays, therefore, have certain definite advantages.

DOSAGE

The development of dosage values has been and still is a difficult problem. Its solution has been considered and developed first from a biological and second from a physical standpoint. The dosage at first was judged by the radiation effect on the skin—epilation or erythema. This was before we had any measuring instruments. Each observer had to take account of the time required with his apparatus to produce epilation or erythema (1st degree), vesiculation (2d degree), or ulceration (3d degree), and be governed by this in other cases. Such information and experience could not be easily imparted to other radiologists nor depended upon as applicable to other machines. At the beginning, nothing was accurate except the factor of time. We had no voltmeters, no milliampere meters, nothing except individual experience. One will find, in the early records of technic, such absurd statements as "The exposure was ten minutes," or "A normal dose was given," just as today we find the equally absurd statements: "Radium was applied for twelve hours" or "25 milligrams were applied for twenty-four hours."

Improvement followed the development of the low-voltage ammeter, the high-voltage milliampere meter, and the voltmeter and we then learned to record the *time, distance, milliamperage, kilovoltage, filtration,* and *size and location of the portal.* With these known factors, a fair degree of accuracy was possible. The dosage could be duplicated and the information could be transferred to other radiologists.



Figs 7 and 8. Fig. 7 shows a lead protecting device 15 inches in diameter with adjustable circular diaphragms in the center, designed by myself in 1903, counterbalanced. The largest opening in this diaphragm corresponded to the size of the largest disk which could be moved out of position completely. Hanging from a string (for purpose of illustration) is a circle of sole leather used as a filter.

Fig. 8 shows the next step in protection furnished by the lead shield fastened to the edges of the lead diaphragm. The use of this was possible only because the shield was insulated by standing on a wood floor.

The early methods of measurement are described by my classmate, M. Kassabian (25) in his book, published in 1907. These included the factors mentioned above and are usually referred to by roentgenologists as "the indirect method" of measuring dosage. The direct method requires a measure of intensity and the total value of radiation reaching the affected tissues—at first, the skin. The first means of measuring the direct amount of radiation on the

skin consisted of disks of barium platinocyanide, the color of which changed from a greenish yellow or lemon color to a deep orange hue. This means of direct measurement was suggested by the fact that barium platinocyanide fluoroscopic screens changed color in this fashion after much use. Sabouraud and Noire, who used roentgen rays extensively for the treatment of ringworm of the scalp, found that when they placed one of these disks midway between the target of the tube and the skin, the change to a deep orange *indicated an epilation dose.* Placed on the skin, it registered, of course, four times this dose. The method required fresh or rejuvenated disks, standard lighting, a standard color disk for comparison (Holzknecht, Hampson, Bordier) (50), and accommodation of the eyes to darkness. These basic requirements were difficult to meet consistently, and the method, therefore, was in general unsatisfactory, though it is probably even now in use. As I remember, it was still employed in 1928 as an auxiliary method in the Curie Institute in Paris. For American use the disks were imported from France and, since they deteriorated on the way, they were less popular here than abroad.

Kienböck (29) recommended the use of strips of photographic paper in small black envelopes. His method required a standard paper, standard developer, standard temperature, and comparison with a standard scale, graded in 10 per cent divisons of the erythema dose. Furthermore, the dosage could be measured only after it was given. I used this method for a number of years, by testing and adapting one of our American photographic papers for the purpose. A small portion of the exposed strip, after being developed, was pasted on the patient's record opposite the factors necessary for the "indirect" method of measurement. These records are still available for observation.

It can be readily understood that none of these methods for dosage measurement was satisfactory. They were inaccurate and difficult to employ. They gave no information regarding the depth value, but concerned only the skin effects.

The *ionization effects* of roentgen rays were reported by Professor Röntgen (58) in his second communication, March 9, 1896. At this early date he wrote: "Electrified bodies in air, charged either positively or negatively, are discharged if x-rays fall upon them; and this process increases with the intensity of the rays." This keen observation, made only a few months after the discovery of the rays, is the basis of our present accurate method of measuring the intensity of radiation at any given point in the air, on the surface of the skin, or at a depth in the tissues or in a phantom, with or without inclusion of the secondary radiation. It took many years to develop equipment for the accurate measurement of this ionization—intensity of radiation—for practical daily use. The next requirement was the development and international adoption of a unit of ionization. I regret that space will not permit a detailed account of the various steps in the development of this unit (see the review by J. Cramer Hudson, 23). The earliest proposal of such a unit of dosage was made by P. Villard (68) in 1908. He defined the unit as "that which liberates by ionization one electrostatic unit of electricity per cubic centimeter of air under normal conditions of temperature and pressure."

As early as 1905, Duane (10) had pointed out the effects of radiation from the walls of the ionization chamber and the methods of eliminating these effects. In 1914, he (11) defined his unit of intensity. Small chambers and methods for practical clinical measurements were developed by Duane (11), Krönig and Friedrich (32, 14), Solomon (64), Villard (68), Glasser and Meyer (16), Behnken (3), and others.

The methods and units of measurement developed by the physicists were so accurate and in such agreement that the Second International Congress of Radiology, meeting in Stockholm in 1928, adopted the "*international unit,*" and defined it as fol-

lows: "The *unit of dose* is that quantity of roentgen radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 c.c. of atmospheric air at 0° C. and 760 mm. mercury pressure such a degree of conductivity that one electrostatic unit of charge is measured under saturation conditions. This unit shall be called the 'roentgen' and designated by 'r'."

The development of an accurate unit of dosage and its international adoption constituted one of the most important steps in the evolution of the scientific clinical use of roentgen therapy. It is true that it required a period of thirty-two years, which again illustrates the truth that many steps and contributions from many minds usually enter into any scientific development.

Originally, even as we do today, we thought in terms of the biological and clinical "erythema dose," but such a concept is inaccurate because it varies with the sensitivity of the skin and with the judgment of the roentgenologist. Great advances have been made, but much investigation is still needed in the development of accurate clinical dosage. This involves a continuation of the collaboration between the clinical roentgen therapist and the physicist. We shall always be grateful to Duane, Failla, Glasser, Meyer, Quimby, Stenstrom, Laurence, Taylor, Weatherwax, and other physicists in this country, and to many in other countries, who have given us so much practical help.

One of the greatest contributions to the scientific advancement of roentgen therapy is the work done by the Committee on Standardization appointed by the radiological societies. We are especially grateful for "Technical Bulletin, No. 1," 1940, prepared by Edith H. Quimby and George C. Laurence (54), who were subcommittee members of the Standardization Committee appointed by the Radiological Society of North America, headed by Lauriston S. Taylor and U. V. Portmann. This *Bulletin*, published in RADIOLOGY (August 1940), contains the basic facts of our technical knowledge to date and its 20 pages of condensed information should be known by every radiotherapist or at least be available for rapid reference. It represents the combined work of our great physicists during the past fifty years.

TECHNIC

In the practical therapeutic application of the roentgen rays, the radiologist must not only take into account the physical factors governing the intensity of radiation and the total amount, but he must consider the biological effect according to the intensity in r units per minute, the duration of the dose if all is given at once—"massive dose"—or the variable effect if the total necessary quantity is given in divided—"fractional"—dosage over a considerable time (two to six weeks), so-called "protracted fractional dose method."

The various methods or technics must be adapted to the conditions which are present in dealing with the individual patient and the special disease under treatment. One must keep in mind the fact that the cells of the body vary in type, and that in disease they have undergone some change, such as inflammation or neoplastic growth, or have assumed abnormal function from causes known or unknown, with consequent disturbance of the organism. Roentgen rays have the power to inhibit function or growth and even to destroy cells, and thus may bring about normal physiologic function.

As a result of clinical observation and researches in biology, it has been found during these fifty years that the different types of cells or tissues of which the human body is composed vary in their sensitiveness to roentgen radiation in the following order: (1) primitive blood cells; (2) germinal cells of the ovary and testicle; (3) blood-forming tissues, including the cells of the red bone marrow, lymphatic system, and spleen; (4) some glands of internal secretion, as the thymus, pituitary, adrenals, and thyroid; (5) the skin and its glands and hair follicles; (6) the abdominal viscera, including the liver, intestines, pancreas, kidney, and uterus; (7)

connective tissue, consisting of muscle, fascia, tendons, cartilage, bone, fat, and nerve tissues.

The reaction or response to roentgen treatment of a disease or neoplasm involving the tissues or organs listed above can be fairly well predicted and the technic must be adapted accordingly. Some lesions are highly susceptible and are radiosensitive if composed of the *sensitive* types of cells, as those of the lymphatic tissue; others are *resistant* if composed largely of connective tissue, such as fibrosarcoma.

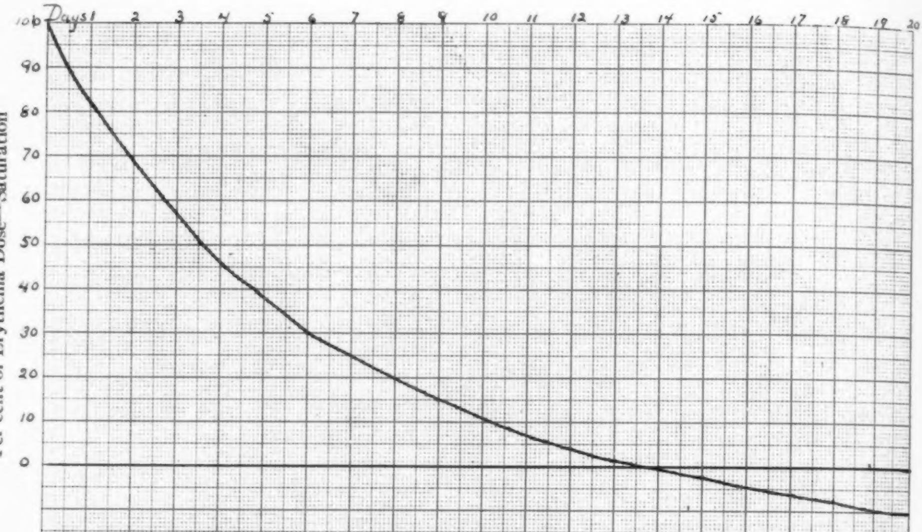
The results obtained during the past fifty years in the roentgen therapy of both superficial and deep-seated disease form the basis for the hope of even greater accomplishment in the future, with improved equipment and greater knowledge of the nature of disease, the biological effects of the rays, and skill in the application of treatment to the individual patient. *Knowledge and skill in the use of this instrumentality are as important as knowledge and skill in the use of the instruments in surgery and are more difficult of attainment because the immediate effects cannot be seen.*

After the physical "indirect method" of measuring dosage had been developed, it was essential to determine the best method of clinical application in each particular disease. Such problems as the following were involved: Should the full dose be applied at one seance or should divided small doses be given? How large should the smaller doses be and what should be the interval? Should a maximum dose be built up in a series? Should this series be repeated, and at what intervals? Should the rays be unfiltered or filtered, and to what extent? After fifty years, these problems are not yet solved. Their solution involves the art of the practice of medicine and the specialty of radiology. Much experience, close observation, and accurate detailed records followed by careful analyses by many competent men have, however, carried us far toward their solution. We are indebted not only to the clinical radiologists, but, as suggested above, to the physicists who have co-operated closely with the physicians in their daily work, as Duane, Failla, Friedrich, Fricke, Glasser, Taylor, Weatherwax, and others.

It has been found that the answer to each of these problems varies with the disease to be treated and with its stage and extent. For example, in the treatment of ringworm of the scalp the "epilation dose" should be given accurately at a single sitting, even though a large area is covered. To take another example, in the treatment of plantar warts, two, four, or even six "erythema doses" should be given at once or in two doses with an interval of two days, depending upon the size, duration, and depth of the lesion. In the majority of diseases treated, on the other hand, the full dosage should be divided, as in all inflammations and most malignant neoplasms. For acute inflammations, the dosage should be very small and given at short intervals, while with chronic inflammation, larger doses and longer intervals are indicated.

In the solution of some of these problems, certain "systems" or general methods of treatment have been developed. None of them is as exact and clear-cut in its application as the literature would imply. The authors themselves will be the first to admit this fact. From the very beginning of roentgen therapy, fifty years ago, the dosage was "fractionated" and more or less prolonged. This was necessary because of our lack of measurement and of clinical knowledge. Priority in the use of or development of the so-called "protracted fractional dose method" belongs to no one in particular. It was used by all pioneer roentgen therapists both in Europe and America.

I learned long ago that it is the *total dosage that gives the late degenerative effects—atrophy, telangiectasis, ulceration, and malignant degeneration.* These may occur when there has never been an erythema or noticeable effect at approximately the time of treatment. This is best illustrated by the damaging effect on the hands of the radiologist of prolonged or frequently repeated minute exposures. Therefore, *no matter how small the repeated doses over any*



Saturation Chart I. Chart for unfiltered radiation prepared April 1920, copied from Kingery's work. It will be seen that if a full erythema dose for 100 per cent is given, the estimated retained effect has been reduced to 50 per cent in three and a half days; in seven days, it has been reduced to 25 per cent, and it is estimated to have reached zero on the fourteenth day. When Dr. Kingery found that a full dose could be repeated on any day within these fourteen days, a dosage could be given which would restore the radiation effect in the tissues to 100 per cent, or any portion thereof desired, according to clinical judgment.

length of time, one must reckon with the total dosage. This is illustrated by the damaging effect of repeated small doses used in the treatment of pruritus ani, especially when given by different physicians.

METHODS OR SYSTEMS OF ROENTGEN THERAPY

The first attempt to reduce the "fractional dose method" to a system was made in 1920 by Kingery (31), who introduced "the saturation method," consisting in the delivery of an erythema dose to the diseased tissue and maintenance of this effect for a certain time by means of additional smaller doses to correspond to the loss in effect during any given period. Kingery apparently made only a preliminary report on the method as it applied to skin diseases.

This method and the principles upon which it is based appealed to me, and I immediately adapted these principles and *applied them with higher voltages and filtered radiation in the treatment of deep-seated malignant growths.* After five years I presented the subject before the International Congress on Radiology held in London, in 1925. I have used the method in principle since 1920 and am still convinced of its value. On re-reading my original paper, I would make practically no change today, except to state that the 100 per cent is built up gradually and the dosage curve can be increased 10 to 15 per cent. If anyone is interested in more details, they are to be found in the article as first presented (44) and in my subsequent observations (45–49).

Kingery said:

"The maintenance of the optimum tissue effect must necessarily depend on the rate at which the effects of the rays are lost. Depending on this time rate is the frequency with which exposures may be repeated, and the quantity that may be administered at each exposure. It seems but logical to assume that tissues exposed to roentgen rays lose that effect in a constant manner. That the greater the concentration of the biochemical products of irradiation, the higher the velocity of loss, would not only seem to follow naturally, but also apparently is borne out by the observations cited below. If this be true, and if we may assume that the rate of loss varies directly as the concentration of some hypothetical

decomposition product, then as this concentration decreases, the velocity of loss will become less in direct ratio. Thus, at such a time as this concentration has decreased by one-half, the velocity of loss will have become less by a similar amount, and so on until the residual effect has become negligible. This rate of loss, theoretically, would represent a logarithmic curve and may be so calculated. Such a curve has been established for many chemical and biologic reactions, which we know as 'mass reactions' and if we may be permitted to draw an analogy, the biochemical change resulting from the absorption of roentgen rays by tissue elements may follow a similar law.

"Should such an analogy be approached, the decreasing residual effect in exposed tissues might describe such a curve as above suggested, and might well lend itself to such a method of representation and computation. In other words, if our analogy is correct, the curve of residual effect in exposed tissues should be a logarithmic curve, and with the velocity of recovery in logarithmic functions, and the intervals between exposures in days, as units, we should be able mathematically, to estimate fairly definitely the residual effect of the rays in the tissues at any given time, and likewise the dosage required at that time, to return the tissue to the saturation stage."

Kingery conducted his clinical observations on *skin diseases, using unfiltered rays.* In such cases the biological effect is assumed to have decreased to a negligible quantity in fourteen days. According to Kingery's chart (Saturation Chart No. I), based on the clinical observation that a 100 per cent dose could be repeated in fourteen days, it may be seen that, at the expiration of three and a half days, the residual effect has been reduced to 50 per cent. After a lapse of another similar period, a total of seven days, it has been reduced to 25 per cent. At each of these points, respectively, a 50 per cent or 75 per cent dose will bring the biological effect to 100 per cent, or the saturation point. With the use of this type of rays for superficial effect, the daily administration of a 25 per cent dose leads, in the course of six days, to 105 per cent and, if further continued, would lead to an overdose. Kingery says: "If, however, only 10 per cent is given daily, the curve does not rise above 60 per cent and one never reaches the optimum or maximum dose."

I commented as follows:

"It must not be assumed, from this latter statement by Kingery, that such small doses can be kept up indefinitely or even that the saturation process can be continued indefinitely or very long. This is the great danger from the method. One must always keep in mind the atrophy, endarteritis, and late degenerative processes, or even early necrosis, which are likely to follow total over-dosage. On the other hand, if the radiation is kept at the saturation point (or as nearly so as the normal tissues will permit) during the brief period of sensitivity of the malignant cells, and while these cells are still undergoing division, it is likely that the disease can be more completely destroyed. At least, this is my opinion."

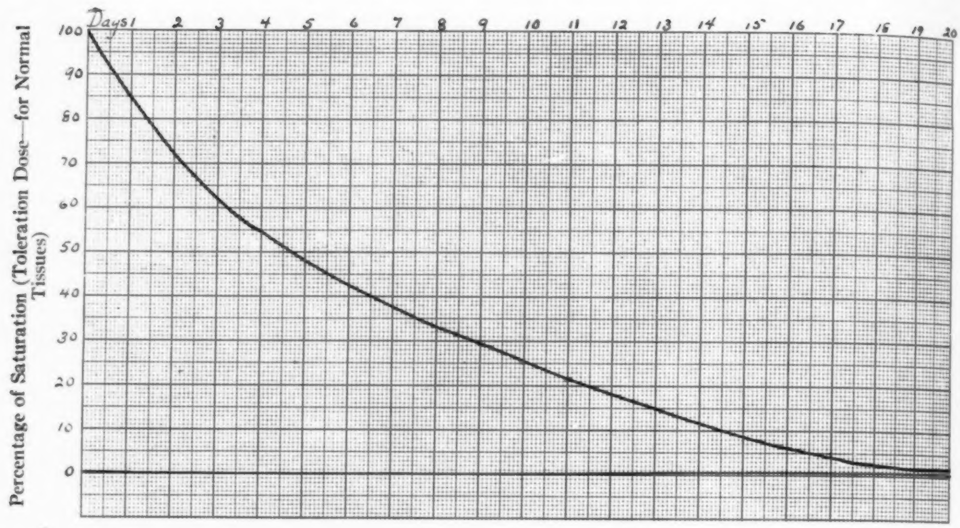
In 1925, I commented further:

"In my work, we have been using this saturation method cautiously more or less during the past five years, giving it up only from time to time while we were trying out the single massive dose methods, which I have now given up excepting where the disease is strictly localized and can be safely overdosed."

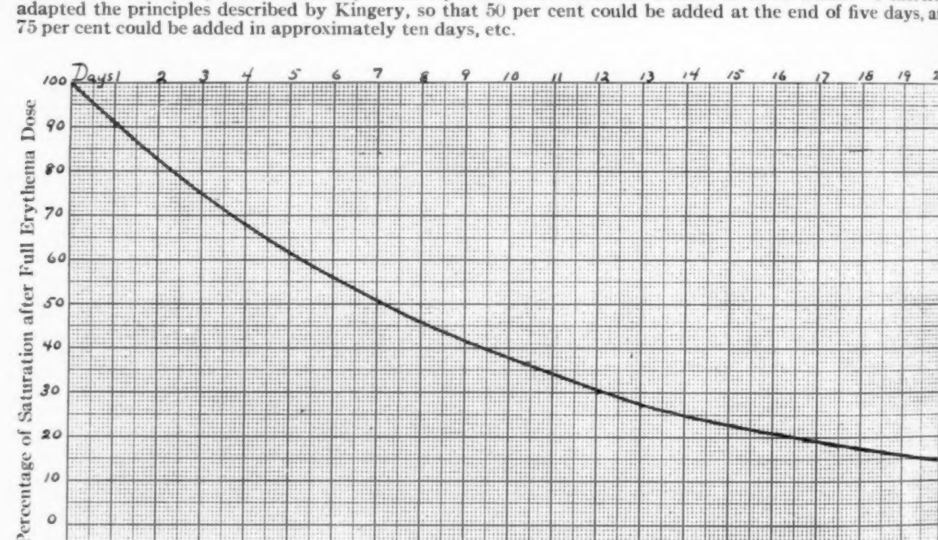
By "saturation" we mean the limit of skin or normal tissue toleration. The saturation curve must, of course, be varied according to the character of radiation used. On the basis of the Kingery principles, I prepared the curves reproduced in Charts II, III, and IV, for use with filtered radiation and higher voltages in the treatment of deep-seated malignant lesions. One must, of course, take into account not only the "saturation" effect on the skin but the dose in the deeper tissue—"the tissue dose" or the "tumor dose," which is usually obtained by cross-firing.

The *massive dose technic* was advocated by L. Seitz and H. Wintz (62) in 1920. By this method, the full "erythema dose," "carcinoma dose," "sarcoma dose," is administered in the shortest possible time. These authors and others in Germany reported remarkably good results from this method, especially in uterine disease, but the technic never became popular in America and the term is now rarely used.

Regaud (55), of Paris, studied the influence of radiation upon cells during the process of division and, about 1914, suggested a technic in which the treatment by comparatively small intensities is extended over a very long period, so that more neoplastic cells are exposed to irradiation during the phases of mitosis, when they are most sensitive to the destructive effects of radiation. This method of using roentgen rays gives a prolonged effect somewhat



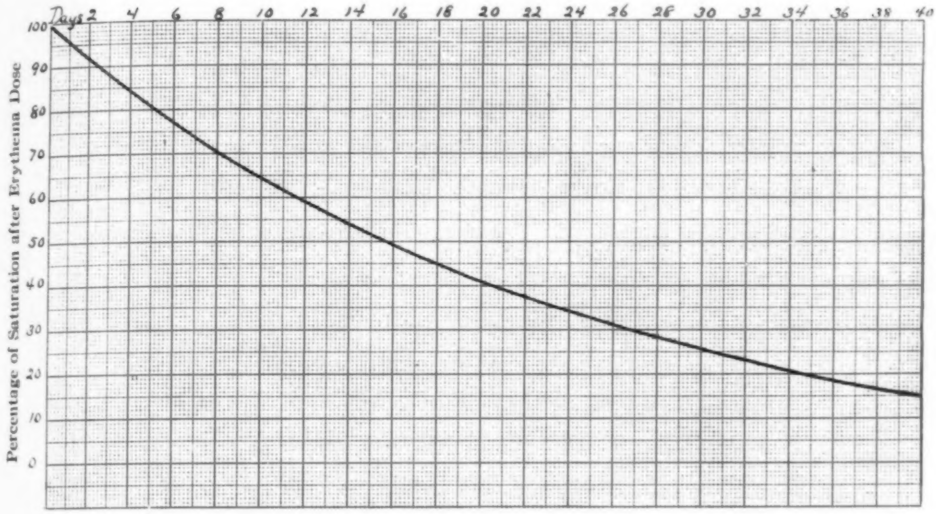
Saturation Chart II. Chart prepared for use with a 9-inch spark-gap (127 kv., 2 mm. aluminum filter). I had observed clinically that I could repeat an erythema dose with such technic in three weeks. I therefore adapted the principles described by Kingery, so that 50 per cent could be added at the end of five days, and 75 per cent could be added in approximately ten days, etc.



Saturation Chart III. Chart for use with 170 kv., 6 mm. aluminum filtration (= approximately 0.23 Ångström mean wave length). With this type of radiation I had learned clinically that I could repeat a full erythema dose in four weeks, and the chart follows the principles illustrated above, allowing a repetition of 50 per cent of an erythema dose in one week, or one-fourth of the former interval, etc.

similar to that obtained with radium, but the roentgen rays have an advantage in that they give a greater depth intensity, due to the greater focal skin distance. This is in accordance with the inverse-square law in the physics of light.

About 1920, Henri Coutard, who was associated with Regaud in the Curie Radium Institute, applied these same principles, with detailed modifications, to the treatment of epithelioma, especially about the face, neck, pharynx, and larynx. His su-



Saturation Chart IV. Chart for use with 200 kv., 0.5 mm. copper filtration, and 2 mm. aluminum, giving approximately 0.165 Ångström units mean wave length, prepared May 8, 1923. I learned from clinical experience that with this type of irradiation, I could repeat 100 per cent of an erythema dose in eight weeks. Therefore, following the above principles, a 50 per cent dose could be repeated in one-fourth this time, or in two weeks, etc.

perior results, particularly in the treatment of carcinoma of the larynx, attracted much attention to this method, which is now commonly referred to as the "Coutard technic." The "Coutard technic" is not a firmly set pattern or established rule. Coutard has himself always adapted the method to the individual case. It is therefore very variable, but certain principles, as those established by Regaud, are followed.

Coutard's method as applied in the treatment of carcinoma of the pharynx, larynx, and tonsils consists, in general, of irradiating the area daily or twice daily through one or more fields, with small individual doses, heavy filtration, and high voltage (originally 200 kv.; now 400 kv.), the dose being "diluted" by increasing the filtration, decreasing the milliamperage, and increasing the distance until, at times, one or two hours or more are necessary to give 150–180 r, and more recently to give 3 r for special effect. The treatment lasts three to six weeks and becomes very costly, but it permits a high total dosage and gives an increasing effect on the disease with relatively less effect on the normal tissue. It is a more scientific adaptation, with more exact measurements and careful observation, of the protracted fractional dose method which was used less accurately by the earliest workers. Whatever arguments there may be against the method, we must all admire the progressively improved results which Coutard and others who have followed his example have obtained. Schinz, in his excellent book (60), has made a careful analysis of his own results obtained by this method during a period of seventeen years.

The clinical dosage problem is being gradually solved but continues to vary with the progressive development of more and more powerful and penetrating rays, such as are now being produced with supervoltage roentgen equipment, by the cyclotron, invented by E. O. Lawrence (33) of the University of California, and the betatron developed by D. W. Kerst (27).

CLINICAL APPLICATIONS

The development of the application of roentgen rays to the treatment of disease began almost immediately after their discovery and has continued up to the present

moment. The literature involves many volumes—both books and periodicals—in all languages. Even a brief record of the contributions would reach encyclopedic proportions. Reference has already been made to Portmann's review of the earlier work (50).

It has been stated that more than 400 diseases have been benefited in variable degrees by roentgen therapy. Skin diseases and malignant growth in all its varieties have probably been the most important fields. Gocht (18) in Germany, was among the first to employ radiotherapy (1897) in the treatment of cancer of the breast. In this country, the first publications on the treatment of cancer were by Johnson and Merrill (24) and by Hopkins (22) in 1900 and 1901. My own experience began in 1901 (41) and was reported before the first scientific meeting of the American Roentgen Ray Society at Buffalo, Sept. 11, 1901. Treatment had been begun Feb. 12, 1901, and I regret to say without any knowledge of the prior reports mentioned above. Early roentgenologists who did much to establish roentgen therapy in this country include Pusey (51–53), Leonard (34), Pancoast (39), Beck (2), and others. These men and their contemporaries throughout the civilized world labored under tremendous difficulties—lack of knowledge, inadequate equipment, and serious danger (see Figs. 4 and 5).

The results obtained during the past fifty years in the roentgen therapy of both superficial and deep-seated disease form the basis for a hope of even greater accomplishment in the future, as we acquire improved equipment, greater knowledge of the nature of disease and of the biological effects of the rays, and increased skill in their application to the individual patient. To repeat: *Knowledge and skill in the use of this instrumentality are as important as knowledge and skill in the use of the instruments in surgery and more difficult of attainment because the immediate effects cannot be seen.*

1930 Chestnut St.
Philadelphia 3, Penna.

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Roentgen Radiations in Biological Research

CHARLES PACKARD, Ph.D.

Marine Biological Laboratory, Woods Hole, Mass.

THE PURPOSE of this paper is to recount briefly the work of those biologists who first studied the effect of roentgen rays on living cells, and to show how the results that they obtained, often under great difficulties, have provided the basis of subsequent investigation. Progress in this field has not been steady. During the first dozen years after Röntgen's discovery, the pioneers carried on exploratory work and saw clearly the fundamental problems which should be solved. But in the next dozen years interest in x-ray research waned, although radiotherapy was advancing rapidly. Biologists turned their attention to radium radiations and with their use made important contributions, especially to experimental embryology. Early in the third decade of the present century x-rays again began to be used in biological research and have been increasingly employed ever since. The literature is now extensive. In this review it is possible to cite only a few examples of research in some of the fields of investigation.

THE EARLY INVESTIGATORS

Those who first tested the biological effect of x-rays on small organisms were interested in determining whether they could be used as a bactericidal agent. Handicapped by the low intensity of the beams produced by the static machines then in use, and by the fact that bacteria are relatively resistant, they were unable to find any effect at all. In 1898, however, Rieder (59) demonstrated that growth could be somewhat inhibited. Biologists then turned their attention to plant cells and to *Protozoa*, whose reactions could be more easily observed. Lopriore in 1897 (46) noted that the circulation of the protoplasm in the cells of certain water plants was accelerated after a moderate exposure to x-rays and that it returned to a normal rate in a short time. A longer exposure terminated in the coagulation of the protoplasm, an observation confirmed a little later by Schaudinn (63), and more recently by others who have used, also, gamma rays and the ultraviolet. The retarding action of the rays on cell division was noted by Koernicke (40), who observed that, if the exposure was not too severe, normal growth might be resumed; the injured cells were capable of recovery. He also demonstrated that seeds exposed after they had taken up water and had started to germinate were more sensitive than dry seeds. In this connection, the observation of Schaudinn is of interest. He found that there was a wide difference in sensitivity among different kinds of *Protozoa*, and that those with highly fluid protoplasm were more susceptible than those with less fluid protoplasm. Thus the physiological condition of the cells at the time of exposure was shown to be a factor in determining sensitivity.

At this time it began to be suspected that x-rays might be the cause of the sterility developing in clinical radiologists. That such was indeed the case was demonstrated by Albers-Schönberg (1) on guinea-pigs and rabbits. When either the male or female was irradiated, no litter was produced. The histologic changes in the irradiated testes were studied the next year by Bergonié and Tribondeau (7), who found that the seminiferous tubules of the rat may be severely injured with the result that spermatogenesis stops completely. The chromatin of the spermatocytes proved to be highly susceptible, but the Sertoli cells remained uninjured. This condition was not permanent, for after some weeks the epithelium regenerated.

That dividing cells are highly susceptible to x-rays was shown by Perthes (55) in his experiments on *Ascaris* eggs. He

concluded that mitosis is the stage of least resistance, but that the eggs could be injured even when exposed during the resting stage. This he proved by keeping them in an atmosphere of hydrogen for some weeks, during which time cell division ceased. On irradiating them, he found that abnormalities developed, although not to so great an extent as when the eggs were exposed during actual cleavage. Regaud and Blanc (58) confirmed these findings and added that the chromatin is the most sensitive part of the cell. It was their belief that the physical and chemical condition of the chromatin is more important in determining sensitivity than the physiological condition of the cell at the time of irradiation. Krause and Ziegler (42) did not agree with this view. In their opinion, sensitivity depends more on the stage of mitosis during which irradiation is carried out than on the kind of cell.

In 1906, Bergonié and Tribondeau (8) summed up the results of their own extensive investigations and those of others on the problem of sensitivity in the following statement: X-rays act with greatest effect on cells whose reproductive capacity is high; on cells whose development involves mitotic divisions (they referred particularly to spermatocytes); and on cells whose morphology and functions are not definitely fixed. These generalizations are true in the majority of cases, but exceptions were pointed out at once. Thus it was shown that bacteria and yeast, although they divide rapidly and continuously, are highly resistant, while some tumors which grow slowly are sensitive.

The effect of x-rays on the course of embryonic development was studied by Gilman and Baetjer (26), who described the various abnormalities appearing in the larvae of *Amblystoma* following exposure of the fertilized eggs. A few experiments on the developing chick indicated that the nervous system was especially susceptible. In the same year, Perthes (55) followed the abnormal development of irradiated *Ascaris* eggs, showing how the chromosomes are injured and behave eccentrically on the mitotic spindle. Similar observations were made on plant cells by Koernicke (40), who used radium radiations. At this time, also, Bardeen and Baetjer (6) noted that x-rays inhibit the process of regeneration in *Planaria*. A little later Bardeen (5), apparently the first to use the rays as a tool of research, fertilized normal toad eggs with irradiated sperm and described the abnormalities which appeared at the time of hatching. In his opinion, the damage produced by the rays could be explained on the assumption that the nuclei were injured and rendered incapable of exerting their normal influence on cell metabolism.

The year 1904 marked the publication of many important contributions to the subject of the biological effects of x-rays. To those already cited should be added the prophetic remarks of the eminent botanist and evolutionist, Hugo DeVries (23): "The rays discovered by Roentgen and the radioactivity of the new element radium have already proved themselves capable of provoking important changes in living organisms. These changes are partly of a retarding nature, and some processes are more sensitive than others. If the same holds good for our dormant representatives in the egg [he refers to hereditary factors] we may hope some day to apply the physiological activity of the rays of Roentgen and Curie to experimental morphology."

Thus in the first dozen years following Röntgen's discovery the foundations of future radiological research were firmly laid. The problems of sensitivity and recovery, of chromosomal abnormalities, of inhibited growth and regeneration, were explored in a preliminary way, and the use of the rays in genetic studies was foretold. But on these foundations very little was built for a long time. War interrupted research, especially in Europe, and it was not until 1922 that an important step forward was taken in the field of radiobiology. From that time until the present, research has been active and rewarding.

X-rays have proved to be a useful tool in

biological research because with appropriate doses the experimenter can produce a wide variety of effects, ranging from reversible reactions, such as a retard in the growth rate or a change in the viscosity of the protoplasm, to irreversible reactions and ultimate death; from minute changes in a single chromosome, which result in alterations in the hereditary material, to a complete breakdown of all cell constituents. Between the smallest dose which produces a recognizable effect and a full lethal dose for the same kind of cell, the difference is great, whereas for other agencies, such as temperature or chemicals, it is comparatively small. Thus 50 r will cause a definite but temporary decrease in the rate of mitosis in tissue-culture cells; a dose of 750 r permanently reduces their rate of growth, while more than 13,000 r must be given to cause a delayed lethal action in all of the cells. It is because of these wide variations in the dose that may be applied within the physiological limits of the cell, and because of great differences in sensitivity, that "it is possible by the use of radiations to destroy certain types of cells, as though by a surgical operation of surpassing delicacy. We can also reach within the cell and effect changes, particularly in the nucleus" (19).

The most obvious effect of x-rays on growing cells and tissues is a retard in the division rate. This may be seen at once in tissue cultures, in which a dose of 240 r produces an immediate drop in the number of mitoses (69). Those cells which have already begun to divide complete the process, but those in the resting stage remain in that condition for some time. Later, if the dose has not been too severe, they resume their mitotic activity.

The retard in the growth rate of seedlings was first employed as a measure of dosage as early as 1915 (60) and has since been extensively used for this purpose. The conclusions drawn by many who adopted this method were faulty, chiefly because too few specimens were used. But with appropriate methods and sufficient numbers, significant results mav be obtained. Henshaw (33) has used the amount of retard as a measure of sensitivity of seeds and seedlings at different stages of development and under various external conditions.

After light doses the retard is temporary and may be followed for a short time by a growth rate even faster than that of the controls. This response was long considered to be due to a direct stimulating action of the radiations (38, 41). It was assumed, without adequate support, that human tissue cells respond in the same way, and the term "stimulating dose" came to be used among therapists. But those who have employed large numbers of seeds and seedlings, in which the effect can be most easily detected, have failed to find evidence of real acceleration. There is no increase in germination, or increase of vegetative parts which results in greater dry weight. An extensive summary of this topic has been made by Johnson (37).

After heavy doses the growth of seedlings and embryos continues for some time, but the organisms sooner or later die after developing into bizarre forms. Knudson (39), however, found that fern spores, after a dose of 50,000 r, lived and grew, although they did not germinate, and that some individuals remained alive and healthy for as long as eighteen months. The ability of adult cells to survive even greater doses is remarkable. The isolated frog heart after receiving 100,000 r maintains its normal rate and amplitude of contraction (64).

The response of protoplasm, first described by Lopriore, has already been mentioned. By means of motion pictures, other reactions of living cells can be seen. Canti (13), who used beta and gamma rays of radium, demonstrated that movement in wandering tissue-culture cells quickly ceased, the cells rounded up, then lost their smooth outlines, and finally disintegrated. Under the intense radiation employed, cells in actual division were unable to complete the process. Vollmar (71) found that a dose of 1,900 r of x-rays, delivered at the low rate of 16 r per minute,

produced about the same results. The cell wall appears to be especially vulnerable, for frequently the cell bursts, allowing the protoplasm to escape. Tumor cells he found more sensitive than normal cells. In them he noted the formation of vacuoles, a response which follows the application of many injurious agents and is associated with the phenomenon of coagulation.

A theory to explain the reaction of cells to radiations was proposed in 1913 by Bordier (11), who noted that proteins irradiated *in vitro* lost their solubility and were precipitated in the form of fine granules. This denaturing effect would account, he believed, for all the observed cellular reactions. The doses he used to produce this effect were, however, far greater than those which injure living cells. Wels and Thiele (73), using a dark-field ultramicroscope, observed the denaturing reaction after much smaller doses than those used by Bordier, but still of considerable magnitude. Wels (72) claims that it can be seen in living cells, but the evidence is not convincing. Should the denaturation occur after small doses, cells would undoubtedly be injured because of the loss of affinity of their proteins for water; but it is by no means certain that it does occur under these conditions.

Heilbrunn (29) has proposed the theory that radiations release bound calcium from the cell cortex, a reaction which results first in the liquefaction of that structure, and probably an increase in its permeability. At the same time there is a general weakening of the cell membrane, as a result of which the cell may rupture. The free calcium ions enter the protoplasm, causing first a liquefaction and then coagulation, accompanied by the production of numerous vacuoles. "Thus we have a mechanism of extreme delicacy, one that can account for the radical colloidal changes observed, without recourse either to the insensitive process of ordinary coagulation or to a purely hypothetical mechanism such as special enzyme effects or point heat effects. This reaction accounts for (though it does not explain) the morphological concomitants of radiation effects, and for the fact that the stimulating and injurious effects of the rays in protoplasm are essentially the same as the effects of other effective physical and chemical agents."

An analysis of some phases of the fertilization process can be made with the aid of radiations, for the nuclei of the gametes can be injured in varying degrees without preventing the cleavage of the egg. In this way information is obtained on the role played by the cytoplasmic portion of the sperm and egg. Following Bardeen's early work, the Hertwigs (35) made an extensive study of the action of radium radiations on both sperm and eggs, and discovered that the greater the dose given to either gamete prior to insemination, the more regular was the course of development. This paradox they explained on the assumption that a moderately injured sperm nucleus attempts to fuse with the normal egg nucleus but, in so doing, interferes with the process of cleavage. After heavy irradiation it initiates development but takes no part in the cleavage process, which is therefore haploid. So also the irradiated egg, after fertilization with normal sperm, divides under the influence of the sperm nucleus, the egg nucleus playing no part in the process.

Simon (65) repeated and amplified this experiment, using x-rays, gamma rays, and ultraviolet rays on frog eggs and sperm. With ultraviolet, the Hertwig paradox was evident, but after treatment with x-rays or gamma rays it appeared only occasionally. Dalcq (22) made a cytological study of this material and found that embryos developing after the ultraviolet treatment had a haploid constitution, as Hertwig postulated, but that those developing after treatment with the shorter radiations, although frequently haploid, were nevertheless abnormal.

That the doses used were too small was shown by Rugh (61), who found that, when irradiated frog sperm is added to normal eggs, the number of embryos that hatch decreases to practically zero as the doses

increase from 15 r to 1,000 r. But with doses greater than 1,000 r there is a rising curve of hatching percentages, which may reach 90 per cent at 50,000 r. These embryos probably have a haploid constitution. Later Rugh and Exner (62) modified the experiment by using bullfrog sperm and leopard frog eggs. Under normal conditions, fertilization occurs but development goes no further than the gastrula stage. There is an incompatibility between the two gametes. With increasing doses applied to the sperm, more and more eggs develop beyond gastrulation, until after a dose of 66,000 r, 80 per cent of the embryos hatch and develop into tadpoles.

It appears, therefore, that by sufficient radiation the incompatible substance in the bullfrog sperm can be destroyed; development is thus a kind of artificial parthenogenesis. According to Rugh, the eggs inseminated with irradiated sperm show a normal cleavage pattern and cleavage rate. But Henshaw (31) reports that sea urchin eggs inseminated with irradiated sea urchin sperm divide more slowly than normal. He believes that the delay "varies with the rate at which some sensitive substrate is being changed or destroyed by the radiation." It is by such experiments as these that the factors involved in the fertilization process can be analyzed.

Changes induced by x-rays in chromosomes have been studied since Perthes (55) first described their swollen shapes and abnormal behavior. Since that time details of the irregular distribution, the formation of multinucleate cells, the occurrence of two or more mitotic spindles, and other reactions have been fully described. Some obvious abnormalities are of special interest from the genetic point of view. "The smaller, less conspicuous and often viable chromosome alterations which have proved to be most valuable and significant cytogenetically, were almost completely overlooked" (28). Three general types can now be distinguished. Chromosomes may become sticky and clump together (2) and, when separating, may spin out chromatin bridges; excessive clumping prevents the completion of mitosis. A second effect is the breaking of chromosomes, either temporarily or permanently; a third effect is the gene mutation, which obviously is not visible.

The sticky quality may be due to a change in the nucleic acid which forms a coat around the chromosomes when they condense preparatory to division (14). This condition was apparently the cause of the genetic results obtained by Mavor (47), who was the first to find hereditary changes in x-rayed *Drosophila*. In his experiments Mavor crossed irradiated females having a dominant character with recessive males. Normally all the progeny should show the dominant character, but he found a number of males which resembled the fathers. This result had been found occasionally in the offspring of non-irradiated parents and is due to the fact that the X chromosomes of the female, instead of separating during the maturation process, remain together. As a result, one daughter cell receives two, and the other none. Radiation increases the frequency of this phenomenon, known as non-disjunction, by about twenty times, probably because the increased stickiness of the chromosomes prevents their separation. Subsequent tests have shown that the increase is proportional to the dose.

The second effect produced by x-rays consists in the breaking of chromosomes. This may be caused by their sticking together in certain places and the subsequent pulling apart under the influence of the spindle fibers. The pieces may become re-attached to the same chromosomes in their original orientation, or in a reverse position; or they may unite with broken ends of other chromosomes. By appropriate breeding experiments, it is possible to determine precisely what chromosomes have been involved in these breakages, in what manner re-attachment occurs, and how much may have been lost altogether. It is beyond the scope of this paper to present the genetic data in support of these conclusions. They are fully discussed, to-

gether with cytological proof of the alterations, by Dobzhansky (24).

The possibility of obtaining gene mutations by the application of radiations, hinted at by DeVries, was explored by a number of investigators, but for some years without success. Morgan and his collaborators tried radium rays on *Drosophila* (50) but were not satisfied that their results were significant. Little and Bagg (45) exposed mice to x-rays and obtained an undoubted mutation, but repetitions of the experiment were not successful. It was not until 1927 that Muller (51), who had long studied spontaneous mutations in *Drosophila*, and had developed elegant methods for their quantitative study, succeeded in obtaining positive evidence that x-rays greatly increase the mutation rate. At the same time Stadler (67) found mutations in irradiated corn and barley, and Goodspeed and Olson (27) in tobacco.

Since that time numerous investigations, in which both animals and plants have been used, have demonstrated that the number of mutations produced by radiations is proportional to the amount of energy absorbed. This is true whether doses of high intensity are used, or divided doses of low intensity are applied over a long period. The mutation is apparently a change in the gene, and is not reversible, that is, a return to the original condition does not normally occur. But subsequent irradiation may occasionally cause a reverse mutation.

The production of these effects is not dependent on the wave length of the beam. The same dose, measured in roentgens, produces the same quantitative effect whether 10-kv. x-rays are used, or highly filtered gamma rays. The rate of mutation is not influenced by the temperature at the time of exposure. Whether the genetic change is brought about by a single quantum hit, or by a chain of events initiated by quantum hits, is the subject of lively debate.

X-rays thus furnish genetics with an invaluable means of studying mutations and chromosomal aberrations of various kinds because they greatly increase the number of such phenomena over that found in nature. These changes in the hereditary material are apparently the same as those that arise spontaneously. The significance of this fact has been commented on by Muller (52), who has made many notable contributions to genetic research. "If spontaneous mutations serve as a basis for evolution (no other basis has been found), then artificially produced mutations likewise must include amongst them artificial building blocks of evolution as good as the natural stones."

THE SENSITIVITY PROBLEM

Differences in sensitivity to radiations among different kinds of cells, in cells at different periods of the life cycle of the organism, and at various stages of mitosis, attracted the attention of the first radiobiologists. Much information on this topic has since been obtained, and theories to explain the phenomenon have been proposed, yet little progress has been made toward the solution of the problem.

That sensitivity changes rapidly during mitosis is clearly demonstrated, but there is little agreement on what stage is the most susceptible. Holthusen (36) concluded that in *Ascaris* eggs the metaphase is the most vulnerable period. This is also the opinion of Whiting (74), who has made extensive experiments with the eggs of the parasitic wasp *Habrobracon*. The difference in sensitivity between the prophase and the metaphase of the first maturation division is truly great. Exposed during the former period, half of the eggs fail to hatch after a dose of 11,800 r; exposed during the metaphase, 450 r suffice to produce the same result. Thus the latter stage is about thirty times as sensitive as the former. Vintemberger (70) states that in the frog egg, sensitivity is low at the prophase and rises until the telophase is reached. The latter is about six times as susceptible as the prophase. Opposed to these views is the opinion that the prophase is the most sensitive stage (69), and that the metaphase is the least susceptible period (43).

During development there is a progressive loss of sensitivity. A single example will suffice to illustrate this point. The eggs of *Drosophila* grow more susceptible from the time they are laid until cleavage ceases, a period of about two hours (54). Thereafter they rapidly become less susceptible, except at the time of gastrulation, a critical period in the development of all kinds of eggs. The median lethal dose for young eggs is 190 r; for the young larva, 1,300 r; for the adult fly about 100,000 r. Woskressensky (75) has presented accurate data which show that the decrease in sensitivity with age is synchronous with a decrease in growth velocity. It is possible to predict the time of death of an irradiated embryo if the dose and the age of the individual at the time of exposure are known. By increasing the normal growth rate, sensitivity should also be increased. Experiments with developing *Ascaris* eggs (36) and *Drosophila* eggs (53) show that this is indeed true. The rise in susceptibility, however, is comparatively small, while the increase in the rate of cell division is large in comparison. The two phenomena are not parallel, indicating that other factors than these are operating.

The generalization of Bergonié and Tribondeau that the sensitivity of cells varies directly with their reproductive capacity and inversely with their degree of differentiation is, with important exceptions, true. This is seen in the results of experiments on regeneration. The early work of Bardeen and Baetjer (6) on fresh-water planarians showed that after exposure to x-rays no new tissue was produced, nor were lost parts restored. The specialized cells of the digestive, muscular, and nervous systems were not injured, but the unspecialized or formative cells which take part in the process of regeneration had lost their power to divide. This was true also of the reproductive cells. More than twenty years later Curtis and his colleagues (20) also using *Planaria*, a favorite form for studies in regeneration, demonstrated that there is a direct relation between the number of formative cells remaining alive after irradiation and the amount of regeneration which ensues. Thus, by taking advantage of the highly susceptible nature of these undifferentiated cells, he was able to show that they are directly concerned in the process of regeneration. The effect of irradiation appears soon after exposure, while the differentiated tissue cells are not visibly altered.

The experiments of Butler and his colleagues (12) on regeneration in amphibian larvae also demonstrate that undifferentiated cells are highly susceptible. When a larval limb is amputated, the cells in the proximity of the cut surface undergo a process of dedifferentiation and form a cap or blastema over it. From this structure, tissues to replace the lost parts are formed by the differentiation of cells composing it. If the blastema is irradiated, its power to differentiate is suppressed, and no regeneration follows. Indeed, the cells in the amputated stump of the limb undergo dedifferentiation and the limb finally disappears. But the larva as a whole is not affected by the doses used. Thus it appears that cells normally somewhat resistant quickly become susceptible when they lose their normal characters and assume a dedifferentiated condition.

It has long been realized that the sensitivity of cells and organisms can be increased or decreased by changing their environmental conditions, particularly the temperature and the state of hydration. The interpretation of the results is not easy. Each change affects vital processes in different degrees; the sum of the various changes is what is observed; the factors which make up the sum are yet to be analyzed.

Various organisms have been irradiated while chilled to freezing temperatures and lower to determine whether their sensitivity is altered when their metabolic and other activities are greatly reduced. Under such conditions frog eggs (4) and seedlings (3) respond in the same way that they do when exposed at normal temperatures; their susceptibility is not altered. But Maxwell and Kempton (48) exposed corn

grains at the temperature of liquid air (−187° C.) and found that, while many were injured, their subsequent growth exceeded that of the specimens irradiated at room temperature. They conclude that the death of the grains which succumbed to the treatment is not primarily due to temperature-dependent thermochemical reactions occurring at the time of exposure, but that factors which produce delayed death are diminished by extreme cold.

The effect of x-rays on a warm-blooded animal chilled during exposure has been studied by Evans and his associates (25), who irradiated rats at temperatures ranging from 37° to 0° C. In all cases the dose was 2,010 r. At the lowest temperature no effect on the skin could be seen; at 17° C. there was a slight epilation, while at 37° C. epilation was complete. The authors believe that lowered metabolism during exposure may be the controlling factor in determining sensitivity.

The experiments with the rat skin and the corn grains are comparable, for in each case the temperature used was the minimum which could be withstood for a short time. But the other seeds and the eggs mentioned above may be frozen for long periods without injury. The fact that this relatively moderate degree of cold has no effect may not be significant, but organisms exposed while chilled to the lowest temperature at which they can survive are less sensitive than they are at their normal temperatures.

When cells are irradiated and then chilled for varying periods, the apparent effectiveness of the rays is diminished; a larger proportion survives than in samples kept at normal temperatures. Holthusen (36) showed this to be true for *Ascaris* eggs. Samples incubated at 22° C. after exposure showed about two and one-half times as many abnormal forms as were found in samples incubated at 2° C. More recently Cook (16) reported that, when these eggs, having received 5,000 r, are kept at 25° C., 1 or 2 per cent develop normally; but if kept at 5° C., 45 per cent are normal. Tissue culture cells respond in much the same way. Strangeways and Fell (68) found that irradiated cultures of six-day chick embryos survive if incubated at 5° C. but die when kept at normal incubation temperatures. These results are interpreted to mean that when cell division and metabolism are at a minimum, cells can partially recover from their injury.

The early observation of Koernicke that seeds show increased sensitivity to radiations after taking up water has been followed by a few attempts to determine more precisely the relation between water content, cell activities, and susceptibility. Petry (56) concluded that sensitivity in seedlings is a function of the degree of hydration. In the presence of water, chemical transformations are induced and these lead to injury. Henshaw and Francis (34) have measured the rate at which water is absorbed by wheat seeds, the rate of oxygen consumption, and the changes in sensitivity during early growth. In the first six hours, water is absorbed rapidly but sensitivity remains almost unchanged. Subsequently the rate of water intake is reduced, while sensitivity shows a notable increase. This occurs before cell division commences. During the entire period the rate of oxygen consumption rises steadily. In the reverse experiment, seedlings were dried and then irradiated. The result was a definite decrease in sensitivity. The authors conclude that no quantitative relation exists between susceptibility and water absorption, oxygen consumption, and mitosis, but that sensitivity rises when water is absorbed and growth commences.

PHYSIOLOGICAL RESPONSES

The way in which x-rays produce their effects has been the subject of much speculation and a considerable amount of research. It is generally agreed that the primary effect is an ionization which tends to transform complex molecules into simpler compounds. Under ordinary conditions of exposure the amount of chemical change is small, but chain reactions may be set up which ultimately affect the entire cell. It is possible, for example, that

some enzymes are inhibited or destroyed, with the result that normal metabolic processes are deranged. These secondary reactions are followed by the appearance of visible alterations. The latter give no clue to the nature of the preceding processes; indeed, they are practically identical with the effects produced by other injurious agents whose mode of action is wholly unlike that of radiations.

It is apparent that x-rays have little or no effect on the rate of oxygen consumption. Bersa (9), who reviewed the literature published up to 1927, stated that no decrease in the respiratory rate of seedlings could be detected until abnormalities in growth appeared. The same result was obtained by Chesley (15) on seedlings and on marine eggs; and by Boell (10) on grasshopper eggs. The fact that growth is impaired before the rate of oxygen consumption is altered makes unlikely any action of x-rays on respiratory catalysts.

The effect of x-rays on glycolysis has frequently been studied, with contradictory results. Scott (64), who reviews the literature on this topic, concludes that this process is not affected, but Crabtree and Gray (17) find that when the rat retina is given no more than 1,000 r, the formation of lactic acid from carbohydrate is checked within a few minutes, although respiration is not affected.

The opinion has prevailed that, in general, enzymes are highly resistant. However, Dale (21) shows that the apparent lack of sensitivity may be due to the experimental conditions usually followed. He finds that 50 r inactivates about 30 per cent of a dilute solution of carboxypeptidase, but when the concentration of the solution is increased 345 times, 100,000 r must be given to accomplish the same result. If concentrations are of the same order as those occurring in living tissues, many catalysts may be affected by comparatively small doses. There can be no doubt that further investigation with appropriate technics will show that the inhibiting action of x-rays on these substances is an important factor in producing the observed alterations in cells.

The fact that during stages of high sensitivity, chromosomes have a high content of nucleic acid, while during stages of resistance they have about half as much, leads Sparrow (66) to conclude that susceptibility can be correlated with nucleic acid metabolism. This is also the view of Mitchell (49), who reviews the literature on the effect of radiations on metabolic processes. About forty years ago Bardeen came to a somewhat similar conclusion. "An injury to the nuclei of cells sufficient to destroy the normal influence on metabolism would suffice to account for all phenomena which have been observed."

RECOVERY

The ability of an organism to recover wholly or in part from x-ray injuries was noticed by Koernicke in 1904, and since that time many examples of recovery in tissue-culture cells and in developing organisms have been described. It is generally assumed that, when the x-ray intensity is low, the rate of repair is sufficient to balance the rate of injury. Thus a dose of 190 r delivered to *Drosophila* eggs at the rate of 5 r/min. or more kills half of the individuals in the sample. But if the intensity is reduced to 2 or 3 r/min., this dose kills only a small proportion. The recovery rate is therefore not far below the rate of injury produced by these low intensities. At the other extreme is the protozoan *Colpidium*, which is not measurably affected unless the intensity is upward of 800 r/min. (18). In this instance the recovery rate is high.

Clinical methods based on the principle that self-repair occurs when low intensities are used have been successful, but only within recent years has any attempt been made to obtain quantitative data in proof of the principle. In 1932 Henshaw (30) measured the rate of recovery in *Arbacia* eggs in a simple and direct way. When the unfertilized eggs are irradiated and fertilized immediately, the onset of

division is delayed, the amount of delay increasing with the dose. This is an obvious sign of injury. If now the irradiated eggs are not fertilized at once but only after intervals ranging from 10 to 220 minutes after the end of the exposure period, the delay in the onset of cleavage is lessened, an indication of partial recovery. The delay is an approximately exponential function of the time interval between the end of exposure and the moment of fertilization. In another investigation, Henshaw found (32) by studying the larvae developing from eggs treated in this way, that the period of recovery is apparently limited to the interval between exposure and fertilization, that is, to a quiescent period.

Quimby and MacComb (57) use a different approach for estimating the amount of recovery in the human skin. The dose needed to produce a definite reaction after two exposures separated by various time intervals is larger than the single dose which will give the same reaction. The difference represents the magnitude of the dose from which the tissue has recovered during the interval. In the first twenty-four hours they find a 67 per cent recovery rate; for the second like period, 31 per cent. Unlike the recovery rate found for *Arbacia* eggs, that of the human skin cannot be expressed by a simple exponential curve.

The conditions in which recovery can occur have received little attention. In view of the experiments already mentioned, in which irradiated cells and organisms were chilled after exposure, the conclusion may be drawn that recovery occurs when mitotic activity is at a minimum. Lea (44), in presenting a theory of action of radiations on biological materials capable of recovery, cites the observation that tissue-culture cells exposed shortly before they are due to divide exhibit a delay in cell division, while those exposed some hours before their normal time of mitosis do not. He remarks that "it is probably safe to say that a given dose of radiation produces the same physical and chemical changes in a cell due to divide an hour hence, as in one due to divide five hours hence, yet on account of the times available for recovery being different, the one cell finds itself unable to commence division at the proper time, while the other cell enters mitosis entirely according to programme."

Marine Biological Laboratory
Woods Hole, Mass.

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1895  1945

Modern Physics and the Discovery of X-Rays

ARTHUR H. COMPTON, D.Sc.
University of Chicago

AMONG THE MOST striking practical developments resulting from the discoveries of modern physics are radio and the atomic bomb. Both are fruits of the discovery of x-rays. In our effort to understand the nature of the world around us, prominent recent advances include knowledge of the arrangement of atoms in crystals and molecules, recognition of the several elemental particles of which atoms are built, the electron and the nucleus, the proton and the neutron, the positron, the mesotrons, and so on, and something of the way in which these particles combine to form atoms. We have learned in the theory of relativity the laws of motion of stars and atoms moving at very high speeds and more precise laws of gravitation. In the quantum theory we have greatly improved our understanding of the nature of light and x-rays and have learned how to describe the motions of atoms and the parts of atoms. All of these new findings stem from Röntgen's discovery of x-rays fifty years ago, and in their development x-rays themselves have been used as a vitally important tool.

We might point out, also, how chemistry, geology, biology, and philosophy have been enriched by Röntgen's discovery. We could show how the electronic tools have stimulated the growth of industry, how the electron tube has made possible not only the radio but also the long-distance telephone and greatly improved telegraphic communication. We could describe the use of x-radiation and radium in the diagnosis and treatment of diseases. All of these have come from the discovery and use of x-rays. They are, however, part of a larger story that we cannot here take time to tell.

Two years before the discovery of x-rays, in his statement of the purpose for which the new Ryerson Physical Laboratory of the University of Chicago was built, Professor A. A. Michelson noted that the fundamental principles of physics had been well established. The future of physics research, he explained, lay in making more precise measurements of the known physical constants. It was for such precision measurements that the new building was designed. This attitude toward physics was common to the leading thinkers of the period, who from the time of Galileo, through Newton, Faraday, Maxwell, and Helmholtz had developed an elegantly organized description of how events in the physical world happen. Ours was a determined world, precisely predictable according to laws that were clearly understood.

X-RAYS

As typical of the scientific work of the period, Wilhelm Conrad Röntgen was then engaged in a careful study of the densities of various crystals. It seems that the immediate occasion for turning his interest to new fields was a publication by Lenard of an experiment with cathode rays striking a thin window from which rays (which came to be called "Lenard rays") were observed to emerge into the surrounding air. Lenard assumed that these were the cathode rays themselves, which penetrated the thin window of the discharge tube and could go a few centimeters further through the air. Röntgen was not so sure. He surmised that perhaps the rays outside the tube were of a different nature, produced possibly by the cathode rays, but of a considerably more penetrating character. He accordingly set up equipment similar to Lenard's but with walls too thick for the cathode rays to penetrate, surrounded his discharge tube with black paper to keep the light from getting out, and had a crystal such as was commonly used to observe ultraviolet light to see what would happen.

How Röntgen saw the fluorescing crystal when the electrical discharge was passed through the evacuated tube is now a matter of familiar history. Otto Glasser sets the probable date of this event as Nov. 8, 1895. From there on, developments were rapid. Before announcing his discovery, Röntgen himself made so thorough an investigation that for the next several years the investigators who rushed into the field added little more than refinement of detail to the statements about the properties of the new rays made in his own initial publications. The effect on a photographic plate, the electrical conductivity of the surrounding air, the slight effect on the retina of the eye, the remarkable penetration but partial absorption of the rays traversing various materials, the sharpness of shadows, unsuccessful attempts to refract, reflect and diffract the rays, even a try at reflecting the rays from a crystal of calcite, were described in Röntgen's publications of 1896. His was a triumph of individually conducted research.

ELECTRONS

It was, however, the uses to which the new rays were put that made this discovery of such extraordinary importance. Within a few months, with the help of x-rays, the existence of ions was demonstrated. For years the idea of electrically charged atoms and molecules had been used in the effort to explain the electrical conductivity of flames and of salt solutions. At a time, however, when one could not be sure even of the existence of atoms and molecules, the theory of ions gained little acceptance. It was when J. J. Thomson and E. Rutherford showed that air made conducting by x-rays could carry just so much current but no more, and that when the exposed air was passed through a strong electric field it was no longer conducting, that people were ready to accept the ionic hypothesis. These were properties predicted on the assumption of ions and for which there appeared no other explanation.

From this discovery of ions came in turn a long line of scientific and practical consequences. Combining the concept of ions with Faraday's laws of electrolysis gave to Arrhenius the firm basis for the theory of electrolytes, which gave impetus to new developments in physical chemistry. Johnstone Stoney noted that this theory required that the charges on each ion should be small multiples of a definite unit, for which he suggested the name "electron." J. J. Thomson surmised that cathode rays consist of tiny "corpuscles" carrying negative charges of this magnitude, and by a brilliant series of experiments measured approximately the charge and the mass of these "electrons." Here was a particle 2,000 times smaller in mass than the lightest atom. What had been named "the thing that can't be cut" is therefore itself composed of smaller parts. Thus came our knowledge of the electron and the beginning of our effort to learn the structure of the atom.

What the discovery of the electron has meant is in itself a story worth many volumes. Its exploitation in the electron tube, through the radio, sound-movies, radar, etc., has changed our social life, our economy, our political development, and has played a crucial part in the outcome of the recent war. On the scientific side, one of the many uses of the electron has been as an object for study while moving at speeds approaching that of light. It was the new phenomena thus presented that led to the theory of relativity, with its far-reaching implications concerning the relations of time and space and of matter and energy.

RADIUM

The early x-ray tubes of the type used by Röntgen glowed with a green fluorescence while emitting x-rays. Though Röntgen himself knew the two phenomena were of entirely different origins, Becquerel started from this observation to search for possible penetrating radiation that might be emitted by natural salts that show fluorescence. Among such fluorescing materials are various compounds of uranium. When these

materials were placed on a black paper-covered photographic plate, they left their images. It was immediately noted that the non-fluorescent compounds of uranium were just as effective as were those that showed fluorescence. However, the discovery of radioactivity had been made. Here were natural materials which of themselves emit rays having effects like x-rays.

There followed an intensive study of the materials that show this remarkable characteristic of radioactivity. In addition to the then familiar elements uranium and thorium, polonium and radium and a score of other new radioactive elements were discovered. Rutherford, Soddy, Mme. Curie, and many others shared in showing how one atom emits a positively charged helium atom or a negatively charged electron and becomes an atom of different chemical properties, a natural transmutation from one chemical element to another. The energies involved in these radioactive changes were a million times greater per atom than those in ordinary chemical processes such as combustion. But no way could be found whereby the rate of transformation from one element to another could be changed. This rate was one of nature's established facts.

By the use of rays emitted by radioactive materials many important discoveries were made. Among them was the fact that each atom has within it a tiny "nucleus," only a ten-thousandth the diameter of the atom itself, which possesses nearly all of the atom's mass. By bombarding various substances with the alpha particles (charged atoms of helium) thrown off by radium, and noting how these particles were deflected by the materials they traversed, Rutherford was able to show that the nucleus of each atom has a positive charge which in electron units is equal to about half of its atomic weight. Around this nucleus circulates an equal number of negative electrons, forming a kind of atmosphere. Thus was blazed a trail which has led to the complete solution of the electronic structure of the atom.

Then came the remarkable discovery of atomic "fission." As a result of shooting an alpha particle from radium against an element of low atomic weight, such as lithium or beryllium, a new kind of particle called a "neutron" is produced. This particle is like the nucleus of a hydrogen atom except that it has no electric charge. If a neutron in turn falls on an atom of the special kind of uranium that has atomic weight 235, the nucleus of the atom is split into two roughly equal pieces and in the process emits further neutrons. If these neutrons are in turn caught by other atoms of U-235 the process is repeated, emitting still further neutrons, and so on indefinitely. Each such "fission" liberates a hundred times as much energy as is given out in the already highly energetic process of radioactive disintegration. This is the atomic chain reaction which goes on explosively in the atomic bomb or in a controllable manner in the chain-reacting piles used to make the plutonium used in such bombs.

Not only did the x-ray tube fortuitously guide us to the hidden store of atomic energy. At many stages, also, studies of x-rays and radioactivity have been intertwined, so that the growth of each subject has been connected intimately with the other. Now in bringing the greatest of all wars to a dramatic close, and in making available a source of energy vastly greater than the fuel at man's disposal, atomic fission has justified all the hopes of the Fermis, Rutherfords, Curies, and Röntgens, whose labors have brought us this Promethean gift.

THE NATURE OF THINGS

For understanding the nature of the world we live in, however, the use of x-rays themselves has during the last fifty years been perhaps the most effective of our methods of research. In 1912 von Laue and his collaborators found that x-rays could be diffracted by crystals just as light is diffracted on passing through a finely woven cloth. This showed at once that x-rays act like waves, just as light does, and also that crystals are indeed composed of regularly spaced layers of particles.

Investigations by the Braggs and others demonstrated that these particles are, in fact, the chemical atoms, and from the manner in which they diffract x-rays it was possible to learn the exact arrangement of these atoms in all the ordinary crystals. On the other hand, led by Moseley, the study of the spectra of elements used as the targets of x-ray tubes showed remarkable results. A regularity appeared in these spectra that made it possible to arrange the elements in a simple series of atomic numbers, starting with hydrogen as one and continuing to uranium as 92. Combined with the theory put forward at the same time by Bohr, it became evident that this atomic number is the number of electrons belonging in the atmosphere of each atom. Thus another important step was taken in learning how atoms are made.

With regard to its effect on our attitude toward the world, the most unexpected and far-reaching discovery of modern physics is perhaps that all the elementary pieces of which things are made have the characteristics of both waves and particles. This paradoxical duality came to light first in experiments on the nature of x-rays, which can be diffracted as waves from a ruled grating or can collide with an electron as one billiard ball bounces from another. This supplied the final evidence needed to establish a general "quantum" theory of mechanics that would apply to particles of atomic size as well as to ordinary things. The theory based on these experiments with x-rays concludes that all particles should show certain characteristics of waves, and that, as a result, the future of events on an atomic scale is predictable only as a statistical probability. Electrons and neutrons and atoms, in fact all kinds of things on which it has been possible to make the tests, show the predicted properties of both waves and particles, and the actions of these things are found to be indeterminate to just the predicted degree.

According to the mechanics that Röntgen knew, as Laplace once said, an intelligence so comprehensive that it would know completely the existing physical state of the world should see both the past and the future as if they were present. The result of the new quantum mechanics is, on the contrary, to show that there is a necessary range of uncertainty in any prediction of the future. For atomic events, and all larger happenings, such as the explosion of an atomic bomb, in which the result depends upon some individual atomic event, the uncertainties thus introduced into future actions are so great that only statistical statements as to what will probably happen have any significance. In the case of astronomical phenomena we deal with occurrences in which so many actions are concerned that the statistical predictions amount to practical certainty. As to the uncertainty of human actions, which depend upon nerve currents involving small numbers of molecules, the degree of uncertainty is unknown. We can merely say that if physics is the sole determiner of human events and our intentions are of no effect, then our future actions are not determined by the present situation, but probably within rather wide limits are a matter of chance. Since the day that Lucretius, in his *De Rerum Natura*, asked how free will was to be reconciled with a world whose atoms are governed by pushes and pulls, men have felt that the determined world of science presents a formidable barrier to belief in the effectiveness of purpose. For those who have grasped the meaning of the quantum mechanics, this barrier has ceased to exist.

HISTORICAL SIGNIFICANCE OF RÖNTGEN'S DISCOVERY

For the person who is concerned with the growth of the distinctively human attributes of man, it is such consequences as these that are the true measure of the greatness of Röntgen's work. If, indeed, science is the great intellectual quest of the modern world, his discovery is one of the greatest achievements of the age. There are those, however, who want to measure importance in dollars, or in the shaping of national destiny, or in terms of human life.

Even in such practical terms the discovery of x-rays should be reckoned as an outstanding event in man's history.

As to human life, one could show that the direct effect of the use of x-rays and radium in diagnosis and therapy has saved a number of lives that is comparable with the number of soldiers killed in a world war. In terms of dollars, the money spent by the United States in building and using radio, radar, and atomic bombs, to mention only a few of the industrial consequences of Röntgen's discovery, has during the recent war been several per cent of the total national income. As to the shaping of political events, it is such factors as the radio with its nation-wide broadcasts of news and music and advertisements, that make our nation a cohesive unit.

Now as we face the future of civilization, what are the great factors that shape our thinking? As one commentator has expressed it, the single fact of the atomic bomb in the hands of America and Britain dwarfs the rest of the war situation into relative insignificance. As a result of the search into the nature of things which x-rays initiated, man has found a new basis on which to organize his world.

It may be correctly said that if Röntgen had not discovered x-rays, someone else would probably have found them within a year. It is true, likewise, that this discovery was itself based on a foundation of painstaking and brilliant researches made by many others in previous years. The discovery nevertheless is properly recognized as marking the beginning of a great new era. First it was the era of modern physics. This then developed into a period of vigorous industrial and social growth such as could not have arisen without the stimulus of the new scientific discoveries.

Perhaps, after all, the greatest human meaning of Röntgen's work lies in the increasing interdependence of people's lives in the world that he has helped to bring into being. This interdependence means a greater need for co-operation. This in turn means that the post-Röntgen world is one in which love of one's neighbor, as expressed in the willingness of each to work for the other, becomes a matter of rapidly increasing value. It is, indeed, such events as these that shape the destiny of man.

Washington University,
St. Louis 5, Mo.

1895  1945

A Half Century of Roentgen Rays in Industry

GEORGE L. CLARK, Ph.D., D.Sc.

Department of Chemistry, University of Illinois

THROUGH FIFTY YEARS the principal applications of roentgen rays have been to the saving of life and to the pursuits of the peaceful activities of men. It is singularly appropriate, therefore, that the deeply sincere and expressed hope that the semicentennial commemoration of Röntgen's discovery might be observed in humble gratitude by a world at peace has been apparently realized. Along with medical, biological, chemical, and physical sciences, engineering and industry owe an incalculable debt to the discoverer, the centennial of whose birth coincides with the semicentennial of the discovery of the rays which bear his name.

It is still too early to evaluate the contribution made by roentgen-ray testing and research to the war effort, since much confidential information has not yet been released, but it is safe to say that an undreamed of peak in industrial application was reached. Undoubtedly roentgen-ray methods have played an essential part in the development of the amazing atomic bomb. On the other hand, much valuable information has been gained to aid in the search for the molecular structure and synthesis of life-saving penicillin, DDT, sulfa drugs, and many other compounds. Bomber and fighter plane motors were doubled in horsepower for the same weight of light alloy castings because roentgen-ray testing and research led to soundness of gross structure and freedom from strain in fine structure. Welded Liberty ships no longer broke in two after roentgen rays were applied to a serious problem of failure. So the wartime story goes—artillery, armor-piercing shells, ballistics from roentgen-ray exposure of a millionth of a second, delicate instruments, storage and dry batteries, synthetic rubber, carbon black, lubricants and waxes, catalysts, chemicals, electron tubes, quartz crystal oscillators for control of radiofrequencies, and innumerable other applications.

How much could Röntgen have foreseen of the practical engineering and industrial uses of the rays which he designated X, at the time of his discovery and at the time of his death? Just as he prophetically warned a complacent world against Adolph Hitler ten years before his rise to dictatorship, so perhaps within his soul the modest physicist of Würzburg could see the march of science and say: "Mine eyes have seen the glory." The jealousies and disappointments which embittered his later years pass away and are forgotten. A half century later he stands in the clear light of fame and acclaim by a grateful world. For roentgen rays are truly one type of light, and light is life.

CLASSIFICATION OF APPLICATIONS

The industrial applications of roentgen rays fall mainly into three classes just as medical uses do. The first of these is radiography, including fluoroscopy—a diagnostic procedure; this also includes the newly developed technic of microradiography. The second, considerably more limited in industry than in the corresponding therapy, involves certain direct chemical and physical effects of the rays. The third application is concerned with the analysis of crystal or ultimate fine structure, depending upon the optical property of diffraction. These three spheres of usefulness will be considered in order, by no means exhaustively, but simply illustrated by examples chosen at random.

RADIOGRAPHY: EXAMINATION OF GROSS INTERNAL STRUCTURE

Engineering materials, especially metal and alloy castings, are constantly a source of weakness. Flaws and cracks in castings are always likely to occur and often are dis-

covered only after a piece has failed, possibly with loss of life, or after expensive machining has been done; it may then have to be scrapped and the work is wasted. If roentgen rays could be used to examine all castings, immediately they would be universally employed, but unfortunately there is a limiting thickness of metal beyond which the rays cannot penetrate. For many years three or four inches of steel was the limit, although greater thicknesses could be penetrated by gamma rays from radium. In the year 1945, however, as a result of the development and commercial use of one- and two-million volt roentgen-ray tubes, this limiting thickness is nearly 12 in. of steel. Metal ingots and castings below this thickness are all capable of roentgen-ray inspection although, owing to the complicated shape of many castings, their examination by x-rays is not always practical.

It is well to remember that radiography is the production of a shadow picture. The shadows exist in the picture because rays are absorbed to different degrees by different media. If we were to radiograph a perfectly homogeneous piece of muscle or steel, we should obtain a photographic plate uniformly blackened because the roentgen-ray absorption would be quite uniform. The absorption of the radiation by any material depends, first, upon the material itself—in general the higher its atomic weight the more absorbent it is—and, second, upon the penetrating power or wave length of the roentgen rays. The latter condition depends, generally speaking, on the voltage which is applied to the terminals of the tube. Thus, according to the first condition, lead is more absorbent than iron, iron more than aluminum, and aluminum more than organic substances such as flesh. At the same time, if we use a tube having a tungsten target, the rays will be more penetrating when generated by 200,000 volts than at 100,000 volts, and so on. If a beam of roentgen rays of suitable penetrating power is passed through an object of varying thickness or varying composition, the emerging rays (which affect the photographic plate) will have different intensities corresponding to the variations in the object, and the result will be a mixture of shadows of varying degrees of intensity. For example, a hidden cavity in a piece of metal means that the total thickness of the material is less at that particular place, and the roentgen-ray absorption will also be less; therefore, we shall obtain more intense radiation in that area, resulting in a darker patch on the negative. If, instead of a photographic plate, we are using a fluorescent screen, we shall see a brighter patch on the screen corresponding to the more intense radiation.

Unfortunately, of the energy represented by the roentgen rays that fall on the photographic film only a very small fraction (less than 1 per cent) has any photographic effect; the remainder simply passes through the emulsion without affecting it. The photographic effect, however, may be increased by the use of suitable intensifying screens that absorb more of the rays and in consequence emit actinic rays which reinforce the photographic image. There are many details of correct technic for obtaining sharp radiographs revealing minute defects which must be learned from theory and experience, just as is true in medical practice. For example, specifications are rigidly set up by the Army Air Forces and other agencies. These involve distance and size of focal spot of the tube, protection of the film from scattered and secondary radiation in the specimen, correct exposure charts, and stereoscopic exposures for locating the depth of a defect. When the object has very irregular edges, it may be convenient to use a wax impregnated with lead or other heavy element. Another method is to immerse the specimen in a liquid having about the same coefficient of absorption.

A certain number of patches or cracks may occur in a casting and still not be serious enough to entail its rejection. The actual significance of the roentgen-ray picture in terms of mechanical strength is a matter for experience in interpretation. The positions and dimensions of metallic

Fig. 1. A. Radiograph of defective aluminum alloy sand casting. B. Defective casting sectioned after radiography. (Courtesy of General Electric X-Ray Corporation.)

flaws may be calculated with great accuracy by stereoscopic methods. Hence the radiograph becomes an infallible guide as to the soundness of material. Usually it may be used as a guide in correcting materials and processes so that they are free from defects and there can be no question of acceptance or rejection. It is doubtful whether dependable castings of the new magnesium alloys ever could have been produced during the war without research guided step by step by radiographic test.

Among the castings and forgings that are at present radiographed on a service routine scale are those for gun carriages, turbine shells and parts, oil stills, airplane parts, locomotive parts, high-pressure steam installations, and expensive steel cylinders, together with many other of specialized importance. The method is in general use in America, and installations are in use for the same purpose in the factories and dockyards of other countries. As already mentioned, the greatly expanded use during World War II of light aluminum and magnesium alloy castings was made possible to a large extent by radiographic control of soundness, both as a routine procedure and as a means of developing correct foundry practice (Fig. 1).

Metallic welding affords another wide field of roentgen-ray usefulness. All welding is liable to faults, and even the best methods depend very largely upon the skill and care of the individual workman. There is no method save radiography of testing a weld without destroying it. As a result of an extensive experience, it is

customary to estimate the mechanical strength of a weld by a mere examination of the radiograph. Inspection of the soundness of welds now ranges from spot welds of thin aluminum foil on airplane wings to welded Liberty ships and the giant penstocks of Boulder Dam and similar structures.

Another application has its main expression in the inspection of assembled articles, such as aircraft instruments, electronic tubes, electric relays and resistances, artillery shells, bombs and rockets (including the proper filling with explosive and incendiary materials and safe inspection of ammunition captured from the enemy), and fuses, where the finished product depends for its proper functioning on the completeness and correct assembly of its internal components. In such cases, elaborate and expensive systems of inspection are often necessary. In many instances roentgen rays afford an accurate means of performing such a check.

Wooden structures, such as airplane and glider parts, railway ties, telephone poles and lead storage battery separators also offer a suitable field for x-ray application. Worm holes, resin pockets, and graining may be determined with great exactness. Roentgen-ray inspection of the roof beams of the aged York Minster in England disclosed in 1938 such a dangerous internal honeycombing from boring of death-watch beetles that immediate replacement was necessary.

In the course of a research on glued joints it was necessary to determine the disposition of the glue. By adding to it a small percentage of a heavy salt, thereby rendering it opaque to the roentgen rays, the dispersion of the glue in the joint was shown with clearness in a radiograph. Much of the success of modern laminated wood as a light and strong structural material is the result of this technic. Motor tires may be examined to determine the position of the cords and the bonding of rubber. Electric insulating materials, such as ebonite and built-up paper materials, may be examined for the presence of impurities and electrically conducting particles. Abrasive wheels have been examined for cracks, and fireclay pots used in the manufacture of glass have been inspected for the presence of harmful metallic impurities. Roentgen rays have also been used by customs authorities and now by the Army and Navy (see *Life*, Aug. 27, 1945, page 110) to investigate the contents of sealed packages. Real pearls may be distinguished non-destructively from imitation by roentgen rays, since the real pearl emits visible fluorescence under the action of the rays. The real pearl also discloses a series of layers or "growth-rings" from the center outward, to distinguish it from the cultivated, or Japanese pearl, which has an artificial center upon which is deposited a thin nacreous layer. Diamonds, which are very transparent to roentgen rays, may be distinguished from imitations, which as a rule are much more opaque. The use of these rays to demonstrate the fit of shoes and boots is now a familiar sight in a shoe store. The exact measurement of the fit of screw threads is a matter that has given rise to a good deal of difficulty; radiography is now being used for this purpose with remarkable success.

Entirely new is the "instantaneous" radiography developed by Westinghouse. A condenser discharge through a special tube provides a roentgen-ray beam of such great intensity that an exposure of the order of a millionth of a second is possible. Thus objects in rapid motion may be radiographed. The most important application has been to the science of ballistics, since the course of bullets through various materials is easily followed.

Prior to 1928, Dr. Heilbron, of Amsterdam, conducted some very remarkable and beautiful experiments with roentgen rays on pictures painted by old masters. The pigments of modern painters are, in general, much less opaque to the rays than those used many years ago. Dr. Heilbron was able to produce evidence of extraordinary alterations having been made in some pictures. In one picture, by Cornelis Engelbrechtsen, the roentgen ray

showed the figure of a vested priest which had been covered at a later date by the portrait of a woman. This hidden feature of the original painting had remained undiscovered for four hundred years. Another picture, a representation of the Madonna by Geertgen van St. Jans, was shown by the roentgen ray to have originally included an infant in the arms of the figure, which had subsequently been painted out. This method has been

Fig. 2. Microradiograph of commonly used wartime aluminum alloy; copper-rich constituent white. X100.

greatly extended by Burroughs of the Fogg Art Museum of Harvard University, Rawlins of the National Art Gallery, London, and others, with the result that a roentgen-ray laboratory is an essential part of any good museum. Even the most famous painting in America, Reynolds' Blue Boy, in the Huntington Gallery, has not escaped. Recently an area above the head appeared to have a peculiar light reflection (*pentimento*). Radiographic examination showed the figure of a man over which the Blue Boy had been painted. The light spot corresponded to the white stock around the neck of this underlying figure on a canvas which had been cut down for the Blue Boy.

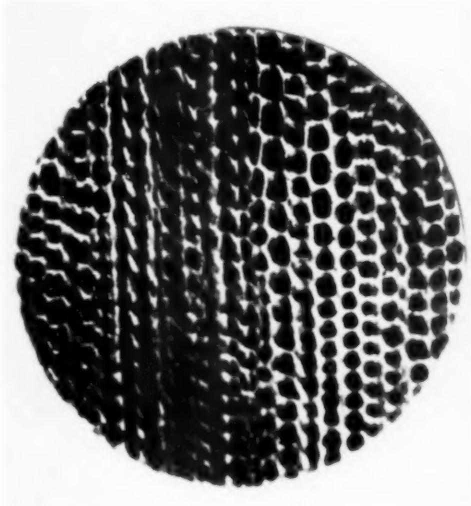

Fig. 3. Microradiograph of tangential section of wood. X*c*.100.

The development of radiographic apparatus has resulted in the production of mobile units and small and portable equipments for various purposes, among which may be mentioned a set for the use of plumbers and builders to enable them to locate the position of wires and pipes in the walls and floors of buildings. Automatic equipment with moving belts permits quality classification, usually by visual fluoroscopy, of many products, making possible elimination of candy containing foreign bodies, separation of juicy and pithy citrus fruits, and detection of damaged or contaminated food products of many kinds. Trucks and railway cars have been equipped with heavier units for rapid transportation to fixed engineering structures.

MICRORADIOGRAPHY

A logical extension of radiography is to the examination of very small objects, the image of which must be enlarged. Since there are no magnifying lenses for roentgen rays, it follows that recourse must be taken to enlargement of radiographs registered on very fine-grained photographic emulsion, such as the Lippmann, or Eastman 548-0. Since 1938, this technic of mi-

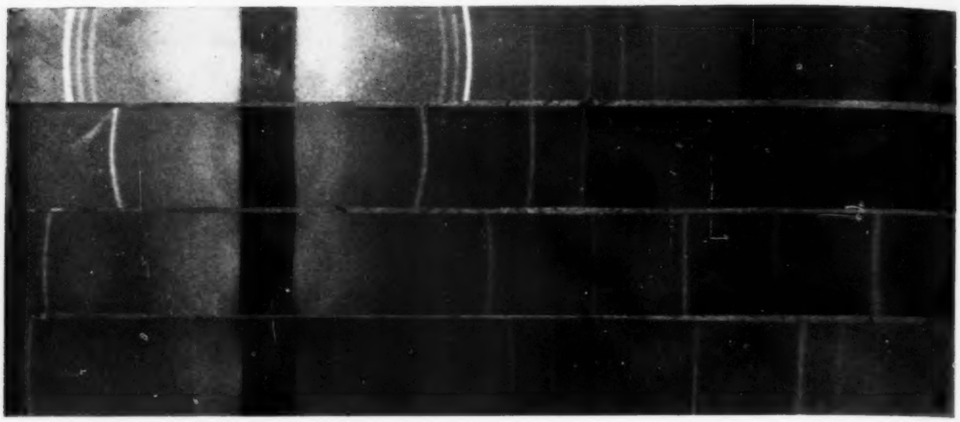

Fig. 4. Diffraction patterns. A. Magnesium (hexagonal close packed). B. Copper (face centered cubic). C. Tungsten (body centered cubic). D. Silicon (diamond cubic).

croradiography has been developed as the result of the work of Clark and his associates at the University of Illinois into a successful and important practical method, especially in the field of metallurgy. The technic is remarkably simple, involving only transmission of roentgen rays generated at voltages below 30,000 volts through a specimen a few thousandths of an inch thick which is in contact with the fine-grained photographic film. The image is then photographically enlarged. Each separate phase in a complex alloy, having a different absorbing power for roentgen rays, can be delineated; by a simple calculation from absorption coefficients, the proper wave length may be selected for maximum differentiation between two or more phases in the most complex bronzes and other important commercial alloys. Biological materials of very small size can be similarly photographed, depending simply on differences in density within the structure or following differential "staining" with absorbing materials. Typical illustrations are the microradiographs of a commonly used aluminum-copper alloy in which the copper appears as white streaks (Fig. 2) and of sections of wood (Fig. 3). A recent accomplishment involved specification of steel for vitreous enameling, since steels of the same composition and structure acted very differently, in some cases causing enamel to shatter. Microradiographs proved that microporous channels could cause diffusion of gases through the metal with disruption of the bond between steel and enamel. The microradiograph supplements the familiar photomicrograph, but has the advantage of a three-dimensional view of a specimen in contrast with the two-dimensional view of an etched, highly polished surface in the photomicrograph. Thus the microradiograph is well adapted for stereoscopy.

DIRECT PHOTOCHEMICAL AND PHYSICAL EFFECTS

Through fifty years there has been accumulating a fund of information on the direct biological, chemical, and physical changes produced in matter by absorption of roentgen rays and consequent liberation of high-speed electrons. The cancer cell is destroyed by such a process; mutations in species are produced by this useful tool of the geneticist; the photographic effect is the best example of chemical change, along with decomposition of a variety of organic compounds and oxidation-reductions. These have considerably greater biological or photochemical significance than truly industrial application. However, a few successes are of unusual interest. There have been many attempts to use roentgen rays to sterilize packages

and bales of such natural materials as dates, figs, cereal grains, and other food products. The organisms have usually been so resistant that impracticable dosages of radiation are required, in comparison with gaseous disinfectants.

Another common application has been coloration of gems, minerals, and glass by irradiation. Unfortunately, many of these attempts have been at the hands of unscrupulous dealers in antiques. An example of this process, however, has proved an outstanding success during the war and saved millions of dollars. The Reeves Sound Laboratories discovered that when quartz oscillator plates, used to control radio frequencies and produced in very large numbers for the Army Signal Corps, are irradiated with roentgen rays, they become smoky in color and at the same time the *oscillation frequencies* decrease. Thus thousands of plates that have been overshot in frequency (or ground too thin, aged, reclaimed) are salvaged. The frequency adjustment is brought under continuous visual control by oscillating the crystal in its holder in the roentgen-ray beam until it reaches the desired frequency. The frequency change brought about by radiation can be reversed and the original value restored by baking the plate at temperatures over 175° C. This process undoubtedly may be applied to a wide variety of other materials. It is to be distinguished from another roentgen-ray technic applied to quartz plates—namely, back reflection control of the original cutting and grinding from natural quartz crystals, as mentioned in the following paragraphs.

ROENTGEN-RAY DIFFRACTION: ANALYSIS OF FINE STRUCTURES OF MATERIALS

Another newer and less familiar branch of roentgen-ray science applied to industrial problems depends upon the fact that solid crystalline materials serve as diffraction gratings for the rays by virtue of the regular arrangement in space of the ultimate atoms, ions or molecules, just as closely ruled lines on glass or metal serve as a diffraction grating and produce a spectrum of ordinary light. This interaction between roentgen rays and crystals was predicted and experimentally proved by von Laue in 1912, and given its simplest expression in the familiar Bragg law: $n\lambda = 2d \sin \theta$, where n is an integer (the order of the spectrum), λ is the roentgen-ray wave length, d is the interplanar spacing or distance between two identical planes of atoms or molecules in the crystal, and θ is the angle of incidence of the beam on this set of planes. Thus every crystalline chemical element or compound produces a diffraction pattern which is uniquely characteristic of the particular kinds and arrangement of atoms or molecules which are the ultimate building blocks of the crystalline architecture.

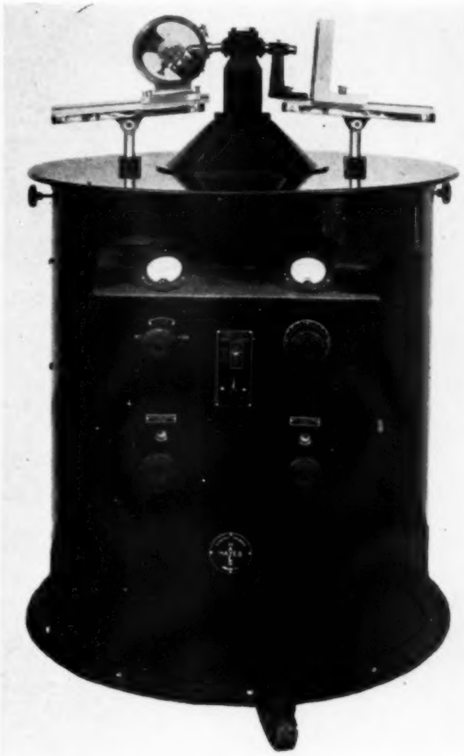

Fig. 5. Typical commercial diffraction unit. (Courtesy of Hayes Scientific Appliances.)

The pattern may be used to identify the solid exactly as it is without solution in a liquid or other change. It is a compara-

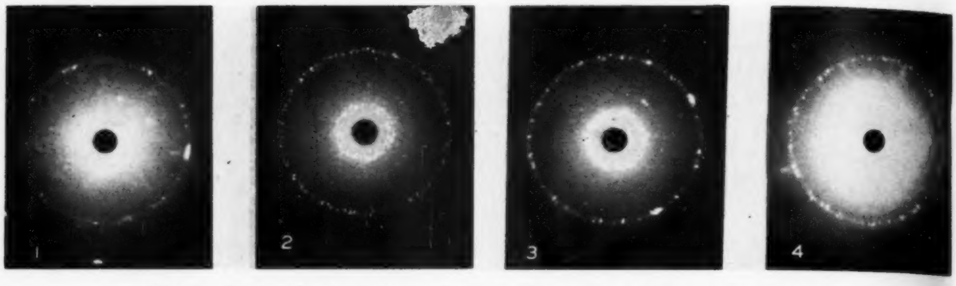

Fig. 6. Back-reflection patterns from aluminum alloy airplane motor casting.

tively simple matter to identify an unknown material if a library of standard patterns of known pure materials is available for matching. To this end the American Society for Testing Materials, in conjunction with the Physical Society of London, has issued a card index of diffraction patterns for about 10,000 compounds, based on the original Dow-Hanawalt Tables. For this identification the material is finely powdered and a so-called powder pattern or spectrogram of sharp lines is photographed. By rapid methods of comparing the three most intense lines with recorded values, the unknown may be readily discovered, if there is a standard pattern for it in the index (Fig. 4).

Thus the practical industrial identification of any solid material may be carried out quite simply without proceeding to the more difficult technics of determining the actual crystalline architecture, or precise scheme of arrangement in space of atoms or molecules, or even of atoms within molecules, particularly for organic compounds.

There are a number of diffraction technics and types of cameras. A carefully collimated train of parallel roentgen rays, usually with one wave length, is directed through, or reflected from, the surface of the specimen, which may be a powder, aggregate, fiber, or single crystal, which may be stationary, rotated, or oscillated. The diffraction pattern is registered on a photographic film, stationary or moving, flat or curved, at a fixed distance from the specimen. In the United States four manufacturers produce, chiefly for industrial use, complete multiple diffraction units on which two or four patterns may be photographed simultaneously (Fig. 5).

Until recently complete structure analyses were largely confined to academic laboratories, from which came a growing new crystal chemistry. Suddenly the problems of identity and synthesis of quinine, penicillin, synthetic rubber, alloys, and a long list of essential materials have required the practical use of the ultimate analyses. The electron density contour map of a complex molecule, derived by mathematical Fourier analysis from intensity data, is now commonly deduced in industrial research laboratories. Many of the newest industrial materials have been the direct result of the guidance of roentgen-ray diffraction research and testing. Natural materials such as minerals, clays and soils, cellulose, proteins and other textile materials are frequently studied.

In addition to analysis of crystalline architecture, diffraction patterns have the important function of indicating texture—the actual condition of a specimen in terms of grain size, orientation, effects of rolling, drawing, fatigue, strain, annealing, aging, and other processes. During the war hundreds of thousands of quartz plates for control of radio frequencies have been properly cut and ground for the Signal Corps of the Army by diffraction control in nearly automatic apparatus employing Geiger-Müller counters for instantaneous check instead of photographic films. Airplane motor castings have been so improved by roentgen-ray back-reflection control (Fig. 6) that strain is eliminated and horsepower

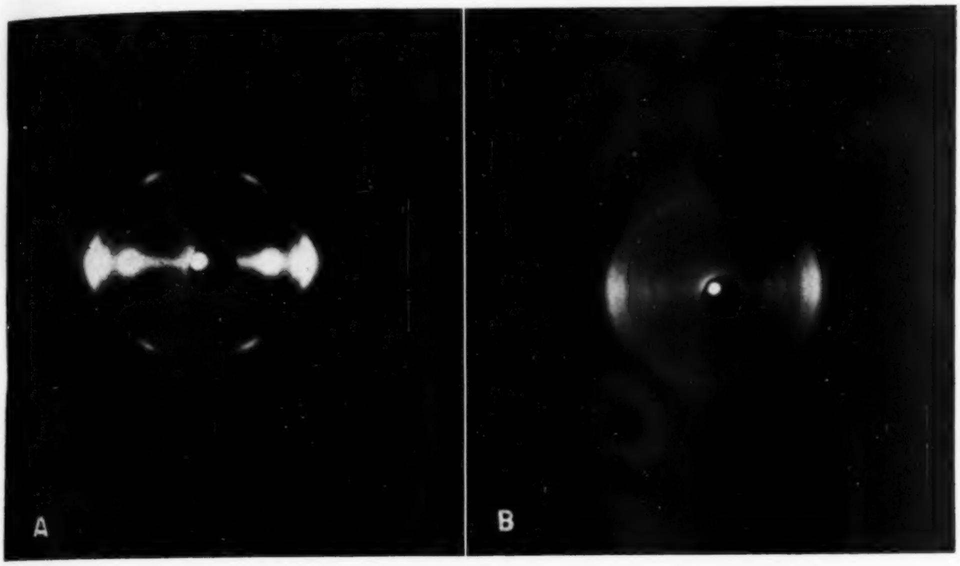

Fig. 7. Diffraction patterns of textile fibers. A. Flax. B. Cotton.

safely doubled for the same weight of light alloys (see 1944 Mehl Award Lecture by the writer, before Congress of Metals[1]). Carbon blacks for rubber reinforcing, charcoal for gas masks, storage batteries (grids and active material), explosives, chemicals, antiseptics and medicinals, waxes and coatings, welded Liberty ships, fluorescent materials, surgical sutures and membranes, natural and synthetic textiles (Fig. 7), elastic polymers and plastics, pigments, electroplatings, lubricants, instrument pivots, abrasives, adhesives, wood and lignin, boiler scale, glass, soaps, parts of V-1 and V-2 German bombs—these are but a few of the materials of industrial and wartime importance to which roentgen-ray diffraction methods have contributed fundamental research information and routine production control; for practical behavior in use so frequently depends on the ultimate structure and texture after gross soundness is assured by radiographic inspection.

In 1945 Dr. C. S. Barrett of the Carnegie Institute of Technology announced a new microscopy of potential value in physical metallurgy and in other fields, which depends on roentgen-ray diffraction. This new adaptation supplements optical and electron microscopy and microradiography. It differs from usual technic in employing a fine-grained photographic plate in contact with or very close to the specimen, upon which a beam of characteristic x-ray strikes. The diffraction image is enlarged just as in the case of microradiography. These diffraction micrographs show the places where inhomogeneous strain is concentrated. Along planes where slip has occurred throughout the interior of crystals and polycrystalline grains there is a local bending or rotation of the crystal lattice. At such points the efficiency of roentgen-ray reflection is increased and a dark line is produced on the photographic plate. Measurement can be made of the amount of rotation (usually less than 0.1°) and the thickness of the distorted layer. Thus strain, plastic deformation, twinning, distortion from scratches and from cutting tools, annealing, recrystallization, coring, clustering of similarly oriented grains, age-hardening, and superlattices are all subjects for investigation by the technic. Sizes and shapes of polycrystalline grains are shown in truly amazing photographs. Since these diffraction micrographs register

[1] Industrial Radiography **3** (No. 2): 13, 1944.

the effects in individual grains (while ordinary diffraction patterns are the summation of effects from large numbers of grains), it is possible to identify microconstituents from the directions of diffracted rays measured with two films at different distances, and application of the Bragg law. Thus non-destructive microanalysis on individual particles is one of the useful applications.

From the foregoing highly condensed and inadequate account, it is evident that volumes would be required to record adequately the achievements of roentgen-ray methods in industry over a half century, with the result that better, safer, more economical materials of everyday life have been produced. Such an attempt is being made in the fourth edition of the writer's "Applied X-Rays" now in preparation, which will be humbly and gratefully dedicated to the eternally living memory of Wilhelm Conrad Röntgen.

University of Illinois
Urbana, Ill.

1895  1945

Organized Roentgenology in America

ARTHUR W. ERSKINE, M.D.
Cedar Rapids, Iowa

THE RAPID advance of roentgenology in America owes much to the association of radiologists in national and local organizations. The three large national bodies are the American Roentgen Ray Society, the Radiological Society of North America, and the American College of Radiology, and it is to these that the present paper is chiefly devoted. These societies, together with the Section on Radiology of the American Medical Association and the American Radium Society, participated in the organization of the American Board of Radiology in 1934 and through their representatives sponsor its activities. Certification by the Board, after meeting its requirements, marks a radiologist as well grounded in his specialty and qualified to practise it in one or more of its special fields.

AMERICAN ROENTGEN RAY SOCIETY

On March 26, 1900, less than five years after Röntgen's great discovery, a group of workers with x-rays met in St. Louis and organized the "Roentgen Society of the United States." Eight states, mostly mid-western, were represented. The meeting was held in the office of Dr. Heber Robarts, editor and publisher of the *American X-Ray Journal*, which had been launched in 1897, and Dr. Robarts was elected President. The first annual meeting of the new society was held in New York, at the Grand Central Palace, Dec. 13 and 14, 1900, and the name was then changed to the American Roentgen Ray Society. Under that name the organization has continued without interruption up to the present time, meeting annually for the transaction of business and the presentation of a scientific program, except on two occasions when wartime restrictions prevented. Since 1939 a series of Instruction Courses has been a popular feature of these annual meetings.

For many years meetings were also held by the Eastern, Central, and Western Sections of the Society. In 1925, however, following the establishment of a Section on Radiology by the American Medical Association, the three Section meetings were discontinued, at about the same time that the Radiological Society of North America gave up its mid-annual sessions.

Those of us who entered the practice of roentgenology after it was firmly established as a specialty in medicine find it hard to evaluate the difficulties that beset the pioneers in our art. Since that winter night when Röntgen first saw on the glowing screen the shadow of the bones of his own hand, the rays which he named "X," the unknown, have appealed strongly to the imagination. The method of their production, their mysterious penetrative power, the crackling sparks, the whir of machinery, the darkened rooms, and the ghostly glow of fluorescent screens, have all suggested that the odor of ozone is not infrequently mingled with that of brimstone. So it is not surprising that for a time after Röntgen's spectacular discovery both the diagnostic and therapeutic use of his weird rays fell into disrepute. The early records of the Society show the names of many applicants, some of whom were accepted, whose only qualification for membership was the ownership of a static machine. But the ancient rosters also list the names of many whom we delight to honor, men who were not only great roentgenologists but were also great doctors, who guarded jealously the honor of the Society and the integrity of their profession. The vigilance of these men, their unselfish devotion to their profession, and the high standards they established and maintained for themselves are responsible in great measure for the respected place roentgenology now enjoys in every field of medicine. Largely as a result of their ef-

forts, the American Roentgen Ray Society became in a decade what it is today, a group of real specialists who respect one another and themselves.

The papers and discussions of the 1900 and the 1901 meetings appeared in the *American X-Ray Journal*. Transactions of the meetings from 1902 to 1905 were published in volume form. In October 1906, the *American Quarterly of Roentgenology* was established by the Society with Dr. Preston M. Hickey as editor, and was published for one year. Transactions again covered the meetings of 1907 and 1908. The *Quarterly* was then re-established, and Volume 2 appeared in December 1909, Hickey continuing as editor. In November 1913, the *Quarterly* took its present form and became the *American Journal of Roentgenology*, New Series, published monthly. This journal has functioned successfully under the successive editorships of Dr. Hickey until 1916, James T. Case until 1918, Harry M. Imboden until 1924, Arthur C. Christie until 1930, and Lawrence Reynolds since 1930. Since the journal became also the official organ of the American Radium Society in 1923, it has been known as the *American Journal of Roentgenology and Radium Therapy*.

Charles C Thomas, of Springfield, Ill., has published the *American Journal of Roentgenology* since 1930, and has taken justifiable pride in its technical excellence. Its paper, typography, and illustrations are of the highest grade and accord well with the notable character of its contents. At the present time there are 4,400 paid subscribers.

Of all the brave spirits who rendered outstanding service to the science and the art of roentgenology in the early years, Eugene W. Caldwell will be longest and most gratefully remembered. Even before the turn of the century he was devoting his entire time to roentgenology. He had a sound scientific education, but he realized early in his career that roentgenology should be practised by physicians, and accordingly worked for and finally, in 1905, received his medical degree. While he was a medical student he published a volume in collaboration with William Allen Pusey entitled "The Practical Application of the Roentgen Rays in Therapeutics and Diagnosis." Perhaps the best evidence of the respect and affection of his colleagues is the fact that after his death the American Roentgen Ray Society established the annual Caldwell lecture. To be asked to deliver this lecture and receive the Caldwell medal is one of the greatest honors that can come to any roentgenologist, or to any scientist in an allied field.

RADIOLOGICAL SOCIETY OF NORTH AMERICA

Unofficially, St. Louis was also the birthplace of the Radiological Society of North America. In the summer of 1915 several radiologists met in the former offices of Russell D. Carman in Olive Street, then occupied by M. B. Titterington, and decided to organize a mid-western society. With the help of George W. Brady, invitations were sent to the radiologists of Missouri, Illinois, and Iowa, and an organization meeting was held Dec. 15 and 16 at the Hotel Sherman in Chicago. There were about thirty charter members. Fred S. O'Hara was elected President. The name chosen for the new organization was the Western Roentgen Society.

There were several reasons for a new society. The American Roentgen Ray Society had developed into an organization of fully trained specialists. Membership in it was not easily acquired, since applicants were expected to have done some valuable original work before they were elected. The annual meetings of the older society were almost invariably held in eastern cities, and the cost, in money and time, of attending them was high. Probably the most compelling reason for forming a new society was the firm belief held by its founders that there should be a place in organized radiology for young men, who should be encouraged to develop within the organization. There was a paragraph in the newly adopted constitution which is still retained. It provides for

members-elect, whose qualifications are the same as those of active members except that the applicant need have devoted the major portion of his time to the practice of radiology for only one year instead of three. The founders and the older members have been proud of the fact that no member, regardless of his obscurity or the modesty of his attainments, has ever been denied the right to raise his voice in either the scientific or executive sessions of the Society.

Because it filled a need, and also because of its democratic spirit, it is not surprising that the new group grew and prospered rapidly. As indicated by the name chosen for it, the founders had expected the Society to be and remain a western organization. The original by-laws contained a provision that the annual meeting should be held in Chicago. In three years, however, it had 472 members in 38 states. It was, obviously, no longer a "Western" Roentgen Society, and the name was accordingly changed to its present one on Nov. 22, 1918.

Although the Society has grown steadily in size and influence, it has not been without vicissitudes. On two occasions it has been rent by internal dissension, in each instance concerned with the publication of its journal. The first official publication of the Society was the *Journal of Roentgenology*, with the late Bundy Allen as editor and business manager. Because of lack of funds, the journal appeared only sporadically from May 1918 to the end of 1919, when its name was changed to the *Journal of Radiology*. This journal was to be published monthly, but only five numbers were printed in 1920. At the annual meeting that year a group of members of the Society subscribed to stock in the Radiological Publishing Co., a non-profit organization established to ensure publication of the journal. For some reason that has never been clearly explained, a small group of stockholders seized control of the publishing company and the journal, and it was not until September 1923, after long, expensive, and bitterly contested legislation, that the Society regained authority over its own journal. At that time RADIOLOGY was started. It has continued since then without interruption under the successive editorships of M. J. Hubeny to 1930, Leon J. Menville to 1940, and Howard P. Doub to the present time.

During the annual meeting of the Society in 1929, the Chemical Foundation offered to subsidize the publication of RADIOLOGY, and the Executive Committee, with some misgivings, recommended that the offer be accepted. It soon became apparent, however, that the officers of the Foundation intended to have a voice in the management of the society. Late in 1931 the Foundation demanded that the Society change its constitution and by-laws and institute a form of government abhorrent to nearly all its members and entirely contrary to the democratic ideals on which the Society had been founded. Although a threat to withdraw the support of the Foundation accompanied the demand, it was promptly rejected, and the relationship between the two organizations was discontinued a few months later.

Although those who were compelled to engage in these controversies may now regret their necessity, the broken friendships they caused, and the violence and bitterness with which they were waged, there can be little doubt that the Society emerged from them stronger and more firmly united than ever before. They at least established incontrovertibly, and it is to be hoped forever, that the Radiological Society will continue to conduct its affairs for the benefit of its members and the science and art it serves, without interference from without or within.

The Radiological Society has always been generous in its support of its official journal. The time, effort, and money expended upon it have been well repaid in the pride and satisfaction the members have in the growth and steadily expanding influence of RADIOLOGY. It now has about 3,500 paid subscribers, and its technical excellence is hardly to be surpassed by any professional publication.

In the summer of 1925, a month prior to the meeting of the First International Congress of Radiology, the Society took an important forward step when it appointed a committee to study various phases of the problem of standardization of x-ray measurements. This committee, perpetuated as the Standardization Committee, has co-operated actively with the National Bureau of Standards and other agencies interested in this important phase of radiology. Its Technical Bulletin No. 1 on "Dosage Measurements," prepared by Dr. Edith Quimby and Dr. George C. Laurence, was approved at the twenty-fifth annual meeting of the Society in 1939.

The year 1938 was notable in the history of the Society for the institution of the Annual Refresher Courses in subjects of fundamental concern to radiologists. These courses, held in conjunction with the Annual Meeting, are conducted by men of the highest qualifications, and large numbers profit by the opportunity they offer.

The by-laws of the Society provide that, by unanimous vote, the Board of Directors may award the gold medal of the Society to "those persons who in the judgment of the Board of Directors have rendered unusual service to the Science of Radiology." The first recipient of this honor was Heber Robarts in 1919. The list of those who have subsequently received it contains many names of men and women who have contributed lavishly to the sum of knowledge of roentgenology. The medal of the Radiological Society of North America is probably the highest honor that any American roentgenologist can hope to receive.

Russell D. Carman was president of the Society in one of the most trying and critical years of its existence. To project his memory and his achievements, the Society established an annual Carman lecture. The first lecture was delivered, by Carman's friend and co-worker, B. R. Kirklin, in 1934. Lecturers in subsequent years have been A. C. Christie, Jas. T. Case, George W. Holmes, Wm. C. MacCarty, Sr., Francis Carter Wood, Ross Golden, Wm. E. Chamberlain, Eugene P. Pendergrass, and Lawrence Reynolds. To be asked to deliver this lecture is a signal honor.

The Radiological Society now has 1,439 members, and it is financially prosperous. While it is probably the most powerful and influential body of x-ray specialists in the world, its strength does not lie only in its numbers and its wealth. It is strong because of its democracy, its unity and solidarity, and the deep feeling, amounting almost to affection, its members have for the organization they have labored to build and maintain. Those who first attend one of its meetings are impressed by the spirit of friendliness that prevails, and they observe that "everybody seems to have a good time." Surely, the hopes, the ideals, and the aspirations of its founders have been satisfactorily and adequately consummated.

THE AMERICAN COLLEGE OF RADIOLOGY

In response to an invitation issued by Albert Soiland, 21 radiologists met in San Francisco on June 26, 1923, to decide upon the feasibility and desirability of forming an American College of Radiology. After a thorough discussion, it was agreed that such an attempt should be made. During the next few months a total of 70 radiologists became Charter Fellows of the College. The first regular Convocation was held early in June 1924, during the convention of the American Medical Association in Chicago. The College is purely an invitational body and Fellowship in it was at first conferred only by the unanimous vote of the Chancellors. Now more than two dissenting votes in the Board of Chancellors, or more than ten negative votes of Fellows, disqualify a nominee for Fellowship. The number of Fellows in the College was originally limited to one hundred, but this limit has been raised several times and was finally removed.

For a number of years after its organization, the activities of the College were limited to an annual Convocation, a din-

ner, and an oration. During that period many radiologists were doubtful that it was useful enough to justify its continued existence, and its death from inanition would not have been surprising. But it did survive, probably because the governing body, the Board of Chancellors, carried out its task of selecting Fellows with conscientious care. Radiologists were indeed rare who could bring themselves to decline the real and implied honor of election to Fellowship.

During the administration of the late John T. Murphy, who was president of the College in 1936, the Board of Chancellors awoke to the fact that the College could, if it chose, exert powerful and much needed influence in two directions which had previously been neglected by the two scientific societies and by the Section on Radiology of the American Medical Association. Soon afterward the following paragraph was inserted into the constitution:

> "Objects. To establish an organization of radiologists for the purpose of advancing the science of Radiology and improving radiologic service to the sick by means of the study of the economic aspects of the practice of Radiology, and the encouragement of improved education facilities for radiologists."

Acceptance of the dual functions of protecting the financial status of radiologists and promoting better radiologic education proved to be just the stimulus the College needed. Its activities and influence began immediately to expand. The accomplishments of the College in various fields during the last ten years are too well known to require enumeration here.

Another change in the constitution of the College which tremendously increased its power was the introduction of a provision for membership in addition to Fellowship. Ethical radiologists who have satisfied the requirements of the American Board of Radiology are eligible for membership. Members have all the rights of Fellows except that they may not hold elective office or be members of the Board of Chancellors.

There are now 488 Fellows and 1,238 members of the College, the total representing more than 90 per cent of all qualified radiologists. These men want radiology to continue to endure as a specialty. In their determination to protect the status of radiologists, they have had to resist those in charge of medical and hospital insurance plans who are attempting to reduce the practice of diagnostic roentgenology to the level of a hospital service. They have had to resist many of their colleagues in their own profession, some of whom sit in the seats of the mighty, who would like x-ray services to be as free to their patients as Wassermann tests are now. So far, their efforts have resulted in a considerable degree of success. Whether they continue to succeed in the trying years that lie ahead through a period possibly of post-war unemployment and depression, depends upon how well we in the rank and file support the College, its Chancellors, its Commissions, and its Executive Secretary.

In 1937, the College decided to employ a full-time executive secretary, and its choice of Mac F. Cahal to fill the position was a particularly happy one. Fully qualified for the position by training and experience, tactful, respected alike by friend and foe, genuinely courteous, yet possessed of unlimited courage, he has been a sword and buckler and an ever present help in time of trouble.

As has already been pointed out, the Board of Chancellors is, in effect, the governing body of the College. It makes all decisions and plans all programs of the activities of the organization. The Board of Chancellors might be likened to the legislative and judicial branches of government. The executive branch is composed of the various Commissions, whose duty it is, with the help of the officers and executive secretary, to carry out the policies decided upon by the Chancellors, under their supervision and under their control. Even so brief a sketch of the College of Radiology as this would be incomplete without some expression of appreciation of the magnitude of the labors of the Chancellors. Those of us who have seen them at work are amazed at

the diligence with which they attack their tasks, the patient study they give their problems, and the wisdom, unanimity, and courage of their decisions.

Finally, while we must admit that the College of Radiology has strayed far from the course plotted by its founders, most of us can agree that the paths it has followed lead in the right directions; that it has assumed desirable functions and fulfilled them with credit to itself; that it has attained a position where it is respected by the medical profession in general, and where it is rendering, and can continue to render, services of inestimable value to the science and art of radiology.

326 Higley Building
Cedar Rapids, Iowa

1895 1945

The Earliest Roentgen Demonstration of a Pathological Lesion in America

ANTHONY C. CIPOLLARO, M.D.
New York, N. Y.

IN THIS YEAR 1945, which marks the one-hundredth anniversary of the birth of Wilhelm Conrad Röntgen and the fiftieth of his epoch-making discovery, it is not amiss to give some thought to the beginnings of radiology in America. It has been the good fortune of the writer to receive a first-hand account of what appears almost certainly to be the earliest use of roentgen rays in this country for the demonstration of a pathological lesion. The incident was described to him by his former teacher, Dr. Gilman D. Frost of Dartmouth College. Dr. Frost's brother, Edwin B. Frost, Professor of Physics at Dartmouth College, was the pioneer roentgenologist, and Dr. Frost was himself present when the film was made.

The actual discovery of x-rays was the culmination of a long and arduous series of experiments conducted in many lands by many scientists. It was on Dec. 28, 1895, that Röntgen submitted his now famous communication to the president of the Physical Medical Society of Würzburg, and within ten days—on Jan. 6, 1896—the news of the discovery was cabled from London to the civilized countries of the world. A translation of Röntgen's original paper appeared in *Nature* (London) on Jan. 23 and was reprinted in *Science* (New York) on Feb. 14, 1896.

So widespread was the interest in the new rays and so great a mass of material was published during the ensuing months that it is impossible to ascertain with absolute certainty when and by whom the first roentgenograms depicting a pathological condition were made in America. The earliest communications to appear in the American literature followed the translation of Röntgen's paper in *Science*, on Feb. 14. Prof. M. I. Pupin of Columbia University, New York, writing under date of Feb. 8, 1896, headed his paper "Röntgen Rays" and, after reviewing the study of vacuum discharges from the time of Faraday, described his attempts to repeat some of Röntgen's experiments.

Pupin made roentgenograms of several objects, including a pair of spectacles in a leather case. He was handicapped, however, by the poor vacuum in his tubes and by the fact that he did not have a static machine. He used a small Leyden jar and covered the ends of his tube with tinfoil. Some of his exposures were of an hour's duration. Pupin describes, also, a roentgenogram of a hand made by A. A. C. Swinton, but this compared unfavorably with a similar photograph made by Röntgen, since the fleshy parts were nearly as strongly marked as the bony structure. This the photographer attributed to over-exposure, but Pupin believed it to be due rather to under-exposure. Like many other early physicists, Professor Pupin foresaw the practical applicability of this new method of photography to surgery, but there is no statement to indicate that at this early date he had made a roentgenogram of a pathological condition.

In the same issue of *Science*, there appeared a short paper by Prof. Edwin B. Frost of Dartmouth College, Hanover, N. H., describing his experimental work with the new rays. It was dated Feb. 4, and the concluding paragraph ran as follows:

> "It was possible yesterday [Feb. 3] to test the method upon a broken arm. After an exposure of 20 minutes the plate on development showed the fracture in the ulna very distinctly."

Professor Frost had available in the Physics Laboratory at Dartmouth several Crookes tubes, a static machine (Holtz), an induction coil, and Grove batteries. One tube proved superior to all others.

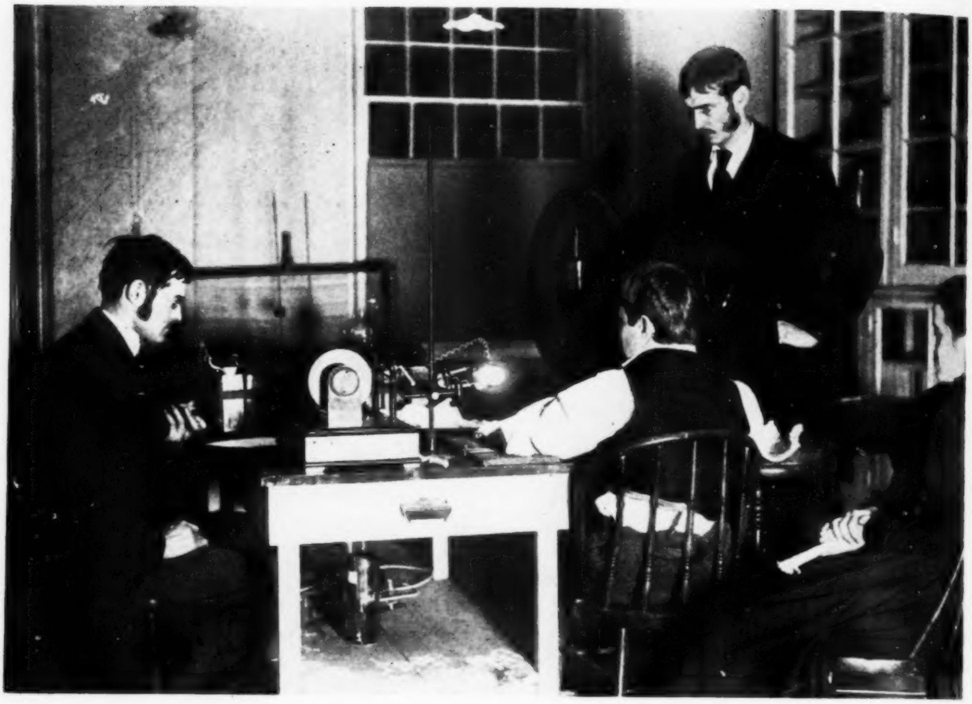

Fig. 1. Photograph taken in the Physics Laboratory, Reed Hall, Dartmouth College, Hanover, N. H., on Feb. 3, 1896. Prof. Edwin B. Frost is sitting, watch in hand, on the left. The patient, Edward McCarthy, is seated to the right of the table. Dr. Gilman Frost is standing to the extreme right, while Mrs. Gilman Frost observes history in the making.

The apparatus is clearly depicted; a special Crookes tube, called a Puluj tube, energized with an induction coil and Grove batteries. The length of exposure was fifteen to twenty minutes. The photographic plate holder is on the table, with the fractured arm resting on it.

This was a Puluj tube, differing from other Crookes tubes in that it had across the interior, in an oblique position, a piece of mica painted with a fluorescent material. As the cathode rays fell upon the phosphorescent salts, a large quantity of x-rays was produced. With an exposure of only twenty minutes, as Professor Frost pointed out, it was possible for him to obtain a clear roentgenogram of a broken arm. The apparatus at his disposal was probably the best in America. He also had the cooperation of Mr. H. H. Langill, the local photographer.

Still another communication in this issue of *Science* was by Prof. Arthur W. Goodspeed of the University of Pennsylvania. A direct quotation serves to establish the time relationship of his experiments. Under date of Feb. 8, he wrote:

"During the past week, experiments have been in progress in the Physical Laboratory of the University of Pennsylvania on the Röntgen phenomena. Impressions of several surgical cases, including deformed fingers, fractures, etc., have been successfully produced."

But while Goodspeed evidently obtained x-ray pictures of pathologic conditions during the week preceding Feb. 8, 1896, he did not publish these at this early date, nor did he mention any specific instance. Incidentally it was he who suggested the term "radiography."

Many articles appeared in subsequent issues of *Science* and in other periodicals, but none, so far as it is possible to ascertain, fixed the date of photographing an actual pathological lesion.

An account of his early application of roentgen rays to a field in which it was to

become a commonplace was furnished by Professor Frost to the *Dartmouth Alumni Magazine* nearly thirty-five years later. It appeared in the April 1930 issue. Professor Frost made no claim to priority in the taking of medical roentgenograms in this country, but the editor assumed that responsibility, and in the light of the present writer's investigations, would seem to be warranted in that assumption. Frost's account of the incident reads:

"A Hanover boy, Eddie McCarthy, had broken the ulna of his forearm on January 19 and Dr. Gilman D. Frost brought him to the laboratory for a test by the photographic method. We secured quite a satisfactory photograph on February 3, as was mentioned in my article in *Science*. This was presumably one of the earliest photographs of a fracture taken in America."

In the Spring of 1896 many roentgenograms were made in the Dartmouth laboratory, and some of these are reproduced in Professor Frost's article, along with that showing the fractured ulna. One shows a metal splinter in the forearm, another a bullet in the knee, and still another a fracture of the humerus.

Six years after Frost's contribution to the *Alumni Magazine*, Arthur Fairbanks, writing in the same publication (February 1936) of Frost's contributions to astronomy and to humane living, said:

"His brother, Dr. Gilman D. Frost, brought him a patient with a broken bone in the arm, and on February 3 he obtained the first x-ray photograph of a fractured bone made in America."

A photograph of the event itself accompanied this account. It was in 1936, also, that the present writer, returning to his alma mater for a brief holiday, encountered Dr. Gilman D. Frost on the Dartmouth campus carrying an envelope containing this same photograph and there heard the story of the first x-ray picture of a broken arm, taken forty years earlier.

In an effort to substantiate Professor Frost's priority in the field of roentgen diagnosis, a careful search of the American literature has been made, with the results recorded above. In the course of these investigations, Dr. Archibald Malloch, li-

Fig. 2. The first roentgenogram of a pathological condition taken in America, Feb. 3, 1896. The fracture lines of the radius and ulna are distinctly shown.

brarian of the New York Academy of Medicine, was consulted. In a personal communication, dated March 13, 1945, he wrote: "We have found no positive statement that anyone in the United States before Edwin B. Frost, on Feb. 3, 1896, took an x-ray picture of a fractured bone." Dr. Otto Glasser, radiation research physicist of the Cleveland Clinic, whose aid was also enlisted, stated that he had been unable to ascertain who was the first in America to take an x-ray picture of a pathological condition. An editorial appearing in the *Journal of the American Medical Association*, April 21, 1945, refers to the claim made "by some, that William J. Morton was the first American physician to make x-ray pictures," but no

dates are given. It would therefore seem that the credit of obtaining the first roentgenogram of a pathological lesion in America belongs to Prof. Edwin B. Frost, the date being established as Feb. 3, 1896.

NOTE: Grateful acknowledgement for their co-operation is due Dr. Otto Glasser, radiation physicist at the Cleveland Clinic; Dr. Archibald Malloch, librarian, New York Academy of Medicine; Dr. Nathaniel T. Goodrich, librarian, Dartmouth College Library; Mr. Charles E. Widmayer, Editor of the Dartmouth Alumni Magazine; and Professor A. B. Meservey, physicist, Dartmouth College.

The roentgenogram of the fractured arm was kindly loaned by Professor Meservey. The original negative, as well as the apparatus used by Frost, is in the museum of the Wilder Laboratory of Physical Sciences at Dartmouth College. The photograph of the procedure itself was the gift of Dr. Gilman D. Frost to the writer, who would here take the opportunity of paying his tribute to that great teacher of practical medicine, one whose instruction was based not on mere pedagogical formulae but on the ripe judgment that comes only with experience.

40 East 61st St.
New York 21, N. Y.

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